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INSTALLATION RESTORATION GENERAL ENVIRONMENTAL
TECHNOLOGY DEVELOPMENT

Final Report

Task 3.   Guidelines for In-Place Closure of Dry Lagoons

Volume II.   Evaluation of In-Place Closure Technologies

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Prepared for:

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
Aberdeen Proving Ground (Edgewood Area), Maryland   21010

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Isolation	Clay	Diversion	
Treatment	Membrane	Slurry Wall	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents a review and evaluation of potential in-place closure technologies. The report serves as a user's manual to guide the installation commander through the evaluation of the applicability of in-place closure. Technologies evaluated include soil cap systems, geotextile fabrics, nonsoil caps and liners, surface-water diversion techniques, slurry walls, grout curtains, well points, and biological, chemical, and physical treatment techniques, including desensitization.

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EXECUTIVE SUMMARY

Background. During past Department of Defense (DoD) production operations at military installations, a common (and accepted) practice was the disposal of process wastewaters in lagoons near the production facility. Explosive wastewaters, heavy metal sludges, and other organic and inorganic wastes have washed out along natural drainage paths or have been placed in lagoon areas. Over the years, some of the wastes placed in these lagoons have migrated or begun to cause groundwater contamination concerns. Many of these lagoons may create problems for excessing actions and may also require decontamination before the disposal area can be declared safe for a specified use by the government or the private sector. In-place closure for some of these lagoons may be a favored technology to mitigate potential migration of contaminants. In-place closure may also represent the safest and most cost-effective closure approach.

The main objective of Roy F. Weston's (WESTON) Task Order 3 contract with the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA), "Guidelines for In-Place Closure of Dry Lagoons," is the development of technical guidelines for closing of waste disposal areas based on the current state-of-the-art technologies. As shown on Figure 1, two major options are available for closure of military installation lagoons, as follows:

(a) Removal and offsite disposal of lagoon contents and contaminated sediments.
(b) In-place closure of the disposal areas to minimize potential future contamination migration.

The Volume I report for this task entitled "Regulatory Requirements Final Report," described site-specific waste lagoon and lagoon environment characteristics, as well as the regulatory requirements for closure. This document, Volume II of the Task Order, develops the in-place lagoon closure guidelines and describes and evaluates the possible application of closure technologies to waste disposal areas at military installations. Closure technologies and techniques are not proposed on a site-specific/installation-specific basis but within a guideline framework that may be applied to any site.

Summary. The technologies for in-place closure comprise three basic categories, as follows:

(a) Lagoon containment.
(b) Waste processing/treatment.
(c) Environmental isolation.
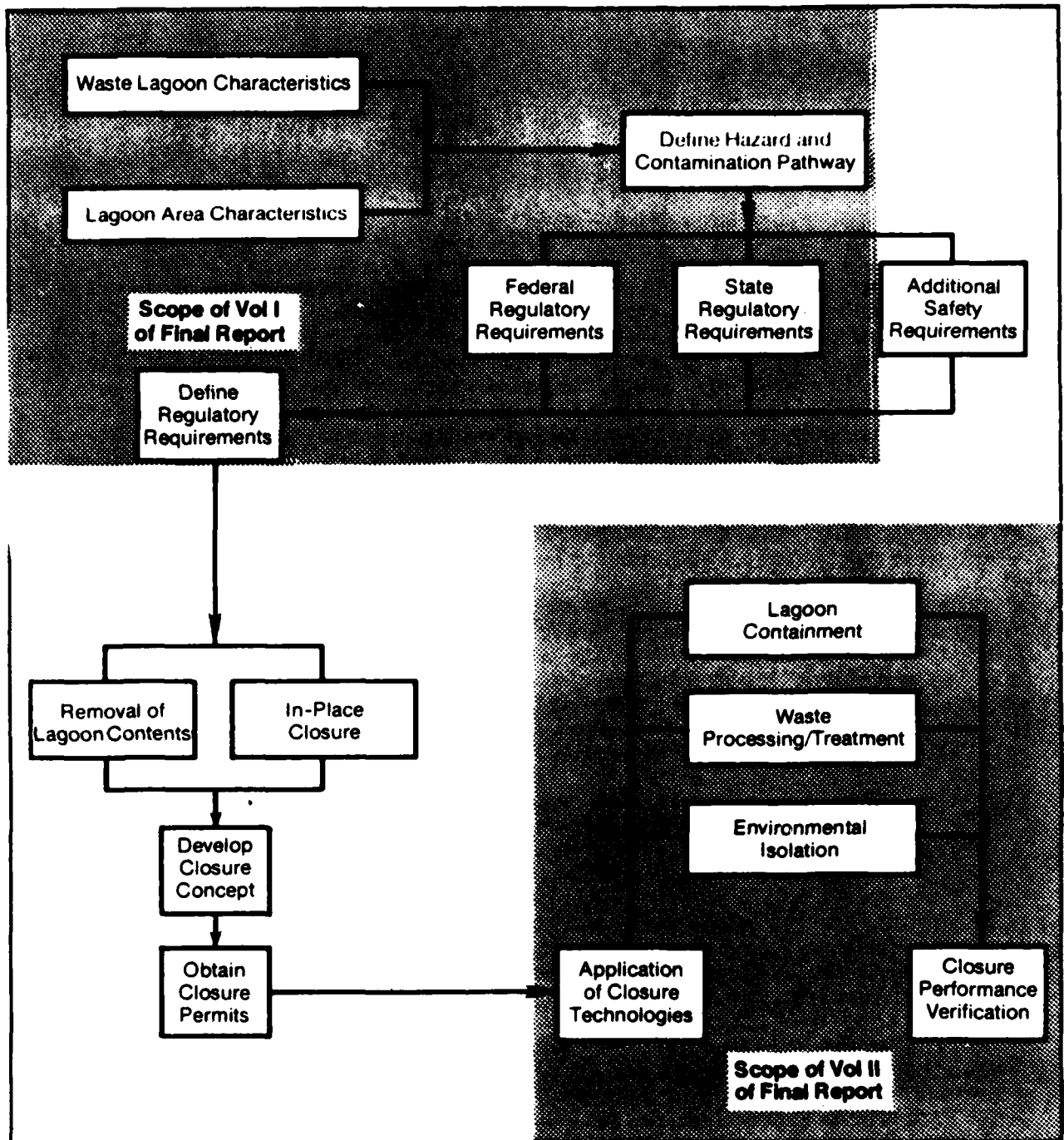
Figure 1 Lagoon closure approach

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More specific technologies within each of these three broad categories are the following:

(a) Containment.

   - Soil cap systems (Section 3).
   - Nonsoil caps and liners (Section 4).
   - Surface-water diversion (Section 5).

(b) Environmental isolation.

   - Groundwater diversion (Section 6).
   - Groundwater flow manipulation (Section 7).

(c) Waste processing and treatment.

   - Solidification/stabilization (Section 8).
   - Chemical, physical, and biological desensitization techniques (Section 8).

Specific remedial-action techniques are presented within each section as methods of achieving the desired objectives of in-place closure. For instance, the discussion of a soil cap system (in Section 3) as a method of waste containment is broadened to include the techniques of multilayer caps, native soil covers, geotextile fabric applications, and bio-barrier applications. Within each section, the closure technologies are presented in terms of system descriptions, functional applications, design and evaluation considerations, performance verification techniques, and limitations. The design requirements and system applications are described in terms of the general waste characteristics and lagoon environment conditions that may be present at military installations and that would be considered in successful implementation of an in-place closure strategy.

Section 2 develops a guideline or "user's manual" for evaluating potential applications of closure technologies. The section presents basic decision matrices and evaluation tables to provide the user with technical guidance toward determining whether in-place closure is a possible alternative and, if so, which remedial-action closure techniques should be considered. Within Section 2, the crucial decision-making questions are addressed in terms of waste-specific concerns (e.g., explosive wastes may require desensitization prior to in-place closure) and site-specific environmental concerns (e.g., ruling out the use of in-place closure when uncontrolled contamination results from waste disposal areas lying within a flood plain or above sinkhole-laden limestone bedrock).

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The primary application of this document is to serve as a guidance manual that provides a decision-making framework for determining if in-place closure is a *viable alternative and* lists and discusses the potential technologies for use with in-place closure. The applications, design considerations, and performance verification techniques for each technology are developed only in terms of the general applicability with specific waste types and the general site conditions required for successful application. Prior to selecting a design for in-place closure, detailed site-specific investigations are necessary to establish the actual disposal practices, waste types, extent of contamination, and critical environmental conditions at a particular military installation. In addition, a detailed engineering investigation is necessary to evaluate the potential remedial closure options for the site-specific conditions and to recommend an appropriate strategy for the site closure.

Recommended research needs. From the results of the technology analysis, the following areas have been identified for additional research needs:

(a)   Compatibility of soil liners (e.g., clays) with leachate from explosive wastes.

(b)   *Compatibility of slurry and grout curtain material with* leachate from explosive wastes.

(c)   Desensitization of explosive waste materials in lagoons in the solid phase mode.

(d)   Use of solidification/fixation techniques to reduce leachability of explosive wastes and possibly render them nonexplosive.

1. INTRODUCTION

1.1 <u>General</u>. The purpose of this report is to present a general remedial action decision-making tool that can be used to evaluate and select technologies for in-place closure of contaminated waste disposal areas. Technologies are addressed to control the various potential waste types to be found at military installations, as well as the potential contamination of the soil, groundwater, and surface water.

1.2 <u>Scope and objectives</u>. In preparing this document, WESTON incorporated five basic objectives into the scope of work. These included:

(a) Assess the physical and chemical waste characteristics to be met for successful in-place closure.

(b) Assess the lagoon area and environmental conditions that must be present for in-place closure to be successful.

(c) Review technologies that can be applied to measure lagoon integrity after closure.

(d) Review technologies that can be used to measure the effectiveness of the lagoon closure to contain the contaminant sources.

(e) Methodology required to verify construction and environmental performance for in-place closure.

To achieve these objectives, the following subtasks were delineated:

(a) Review of waste lagoon characteristics data (incorporated into Volume I).

(b) Establish site-specific lagoon area conditions (incorporated into Volume I).

(c) Review of applicable state and Federal regulations for hazardous waste disposal (incorporated into Volume I).

(d) Review of lagoon closure technology (incorporated into Volume II).

(e) Establish lagoon guidelines (incorporated into Volume II).

(f) Establish performance verification technology (incorporated into Volume II).

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1.3 <u>Literature search</u>. To gather information on current state-of-the-art closure technologies, WESTON performed an extensive literature search. The searching process included a review of existing DoD research projects, as well as an extensive application of key word computer search patterns. The search was conducted during the early phase of this Task Order and produced a large listing of potentially applicable journal articles and research reports. The files accessed during the computer search routine included the following:

(a) Pollution abstracts.
(b) NTIS (National Technical Information Service).
(c) Compendix (Engineering Index).
(d) Enviroline.
(e) Georef.
(f) Geoarchive.
(q) Cris/USDA.
(h) DROLS (Defense Research On-Line System).

Once the literature search data were compiled, it was reviewed for inclusion of pertinent articles into the Volume II document. WESTON intended to review existing and proven closure technologies as well as recently emerging and innovative approaches. Technologies were identified in all areas addressed in the report, including soil cap systems, nonsoil caps and liners, surface-water diversion, groundwater diversion, groundwater flow manipulation, and in-situ processing/treatment techniques. The key references utilized in the evaluation of in-place closure technologies are included at the end of each section.

2. APPLICATION OF IN-PLACE CLOSURE REMEDIAL ACTIONS

2.1 <u>General</u>. The purpose of this document is to provide a decision-making handbook that can be used to evaluate and select technologies for in-place closure of contaminated waste disposal areas. Technologies are presented and evaluated herein to control the waste types encountered at military installations as well as the potential contamination of soil, groundwater, and surface water. A guidance manual for selection of various in-place closure techniques is described in subsection 2.2, and an overall summary and evaluation of the specific remedial actions is presented in subsections 2.3 and 2.4. Finally, subsection 2.5 presents trial scenarios for in-place closure, in which the guidance manual decision matrices are used to evaluate potential scenarios for closure.

The guidance manual can be used by installation decision-makers to generally assess the applicability of remedial action categories, based on site-specific waste characteristics and site conditions. The highlights of the detailed remedial action descriptions (Sections 3-8) are outlined for the various technologies through evaluation matrices within subsection 2.3. These specific technology evaluations can be used in conjunction with the general guidance manual to assess the applicability of in-place closure at a particular military installation. It should be noted that these technology-specific evaluations are still generic in nature, and detailed site-specific and waste-specific evaluations would be required to fully characterize the applicability of in-place closure.

2.2 <u>Guidance manual for in-place closure applications</u>. Subsequent sections of this document present descriptions of current state-of-the art technologies for in-place closure of contaminated areas. These technologies are discussed in terms of an overall process description and a general evaluation of appropriate design and performance verification techniques. One of the overall objectives of this Task Order is to prepare general guidelines for in-place closure of waste disposal lagoons. To this point, the evaluation of technology applications has been confined to the general waste and lagoon environment characteristics for each of the six major technology categories.

This section presents an overall decision-making framework for the evaluation of lagoon closure applications. The technologies are described in terms of their general use for mitigating environmental contamination problems. The scale of the evaluation is broadened from technology-specific (as described in

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Sections 3-8) to system-specific, where groups of technologies can be applied to solve the varied contamination problems of interacting environmental characteristics.

The Volume 1 deliverable for this Task Order was presented as a background review document of selected Army installations to describe waste lagoon characteristics, lagoon area (environmental) characteristics, and pertinent state and Federal hazardous waste regulations. From that information, the following general conclusions were drawn in terms of existing contamination concerns at these Army installations:

    (a)   General categories of waste lagoon characteristics:

        - Explosive wastes in unlined lagoon areas.
        - Explosive wastes in natural drainage ditches.
        - Explosive wastes in lined lagoons.
        - Nonexplosive wastes in unlined disposal areas.
        - Nonexplosive wastes in lined disposal areas.

    (b)   General categories of environmental characteristics:

        - Average annual precipitation.
        - Soil type and permeability.
        - Type and thickness of unconsolidated sediments.
        - Type and depth to bedrock.
        - Depth to groundwater.
        - Groundwater use.
        - Flooding potential.

This section of the document describes the methodology that can be followed to evaluate and implement remedial action closure approaches at Army installations. Matrices, figures, and tables are provided as decision-making tools to help evaluate the impacts of the waste lagoon and environmental characteristics on in-place closure. This section is set up to address four basic aspects of the assessment of in-place closure techniques and to enable an installation commander to progress through the evaluation from general considerations to site-specific applications. This section describes the following:

    (a)   General evaluation approach.
    (b)   Assessment of contaminant pathways.
    (c)   Technology evaluation.
    (d)   Development of trial closure scenarios.

    2.2.1   General evaluation approach. Figure 2 presents the basic decision-tree matrix that can be incorporated as a general

Closure/post-closure phase

Long-Term Monitoring/Maintenance

Remedial Action Implementation

Performance Verification

Technology evaluation phase

Evaluation and Design of an In-Place Closure Approach

In-Situ Processing/Treatment

Groundwater Flow Manipulation

Groundwater Diversion

Surface-Water Diversion

Noncoil Beds

Soil Cap Systems

Can Remedial Action Reduce Concerns?

Yes

No

In-Place Closure is Not an Option

Site assessment phase

Evaluation of Impacts of Site Conditions on In-Place Closure

Groundwater Contamination

Annual Precipitation

Soil Characteristics

Bedrock Porosity

Flooding Potential

Do Waste Characteristics Prohibit Closure?

No

Yes

Do State Regulations Impact Closure?

No

Yes

Can Processing/Treatment Reduce Hazard Potential?

Yes

No

In-Place Closure is Not an Option

Determine Waste Characteristics

Determine Lagoon Environment Characteristics

Figure 2. Basic decision matrix for evaluating in-place closure remedial action.

framework for evaluating in-place closure remedial actions. Figure 2 can serve as a guidance matrix for an installation commander to assess the application of closure technologies. The matrices presented in subsequent subsections provide greater detail for this evaluation. The following three phases of this assessment are portrayed:

(a)   Site assessment phase.
(b)   Technology evaluation phase.
(c)   Closure/post-closure phase.

Within the site assessment phase, the installation's waste lagoon characteristics and lagoon environment characteristics are determined as an initial work item. For the most part, the information gathered under the USATHAMA Phase I and Phase II installation assessment reports can provide the basis for understanding these installation-specific characteristics. In addition to this information, the impacts of regulatory requirements on site closure must be understood, and an evaluation of the impacts of site-specific conditions on in-place closure must be conducted. State regulatory requirements may serve as an ultimate constraint on in-place closure (see Volume 1 of this Task Order), as is the case with in-place closure of a reactive waste that cannot be treated/desensitized to eliminate reactivity. As Figure 2 indicates, in-place closure in this case is not an option.

Once the regulatory impacts are understood and conditions are favorable for closure, the interaction of the lagoon environment characteristics must be evaluated. This represents the key component to accomplishing the second phase of the decision tree matrix outlined in Figure 2, the technology evaluation phase. The crucial consideration here includes the evaluation of the applicability of various in-place closure approaches to solving the environmental concerns of waste management. Technology evaluation, design and construction, and performance verification are keys to the success of the in-place closure approach. Each of the six closure technology categories (evaluated in general in subsection 2.3 and discussed in detail in Section 3 through Section 8) must be evaluated in terms of its application as a remedial-action approach to eliminating the environmental contamination concerns. Decision-making guidelines for completing the technology evaluation phase are expanded upon and discussed in greater detail in this section.

The final evaluation stage presented in Figure 2 is the closure/post-closure phase in which remedial-action implementation and long-term monitoring/maintenance considerations are addressed. The success of many remedial-action approaches may hinge on the ease of implementation and the degree of long-term requirements for monitoring and maintenance.

2.2.2 Assessment of contaminant pathways. The site assessment phase and technology evaluation phase requirements shown on Figure 2 are expanded upon and described in detail in this subsection. Six matrices, Figures 3 through 8, are included as decision-making guidelines for evaluation of the site-specific and technology application considerations. Each matrix is designed to aid the decision-maker in assessing the application of various in-place closure approaches, and each addresses an individual contaminant pathway that can be impacted through closure. The six contaminant pathway considerations are as follows:

(a) Waste and lagoon area characterization (Figure 3).
(b) Surface area conditions (Figure 4).
(c) Surface infiltration considerations (Figure 5).
(d) Subsurface soil characteristics (Figure 6).
(e) Hydrogeological conditions (Figure 7).
(f) Groundwater conditions (Figure 8).

2.2.2.1 Waste and lagoon area characterization. The matrix shown in Figure 3 is used to determine whether any waste type or environmental characteristic exists that would limit the application of in-place closure technologies. The inputs to this decision matrix include an evaluation of the available site-specific background information, the performance of field investigations to characterize the wastes, soil, groundwater, surface-water, and air conditions, and an evaluation of applicable Federal and state regulatory requirements for hazardous waste management. The decision variables in the matrix describe the constraints that the waste material may pose for in-place closure. The installation commander can work his way through the decision variables, concluding with matrix outputs that lead to either the determination that in-place closure may not be an option or into the evaluation of alternative closure options. If the waste characteristics are not constraints on in-place closure (either by definition or after waste processing/treatment), Figures 4 through 8 should be used to evaluate the alternative closure options for the waste area.
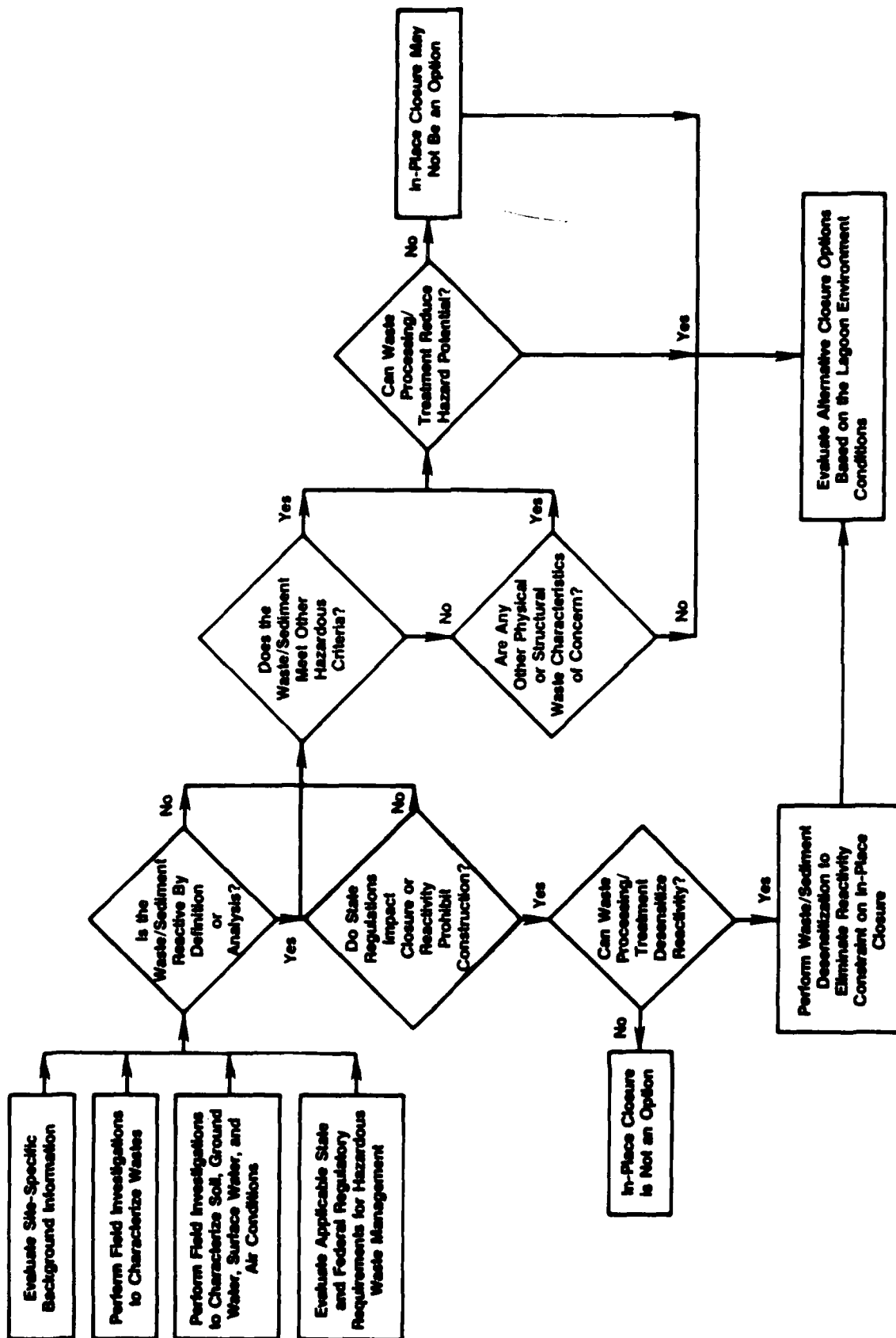
Figure 3. Waste and lagoon area characterization.

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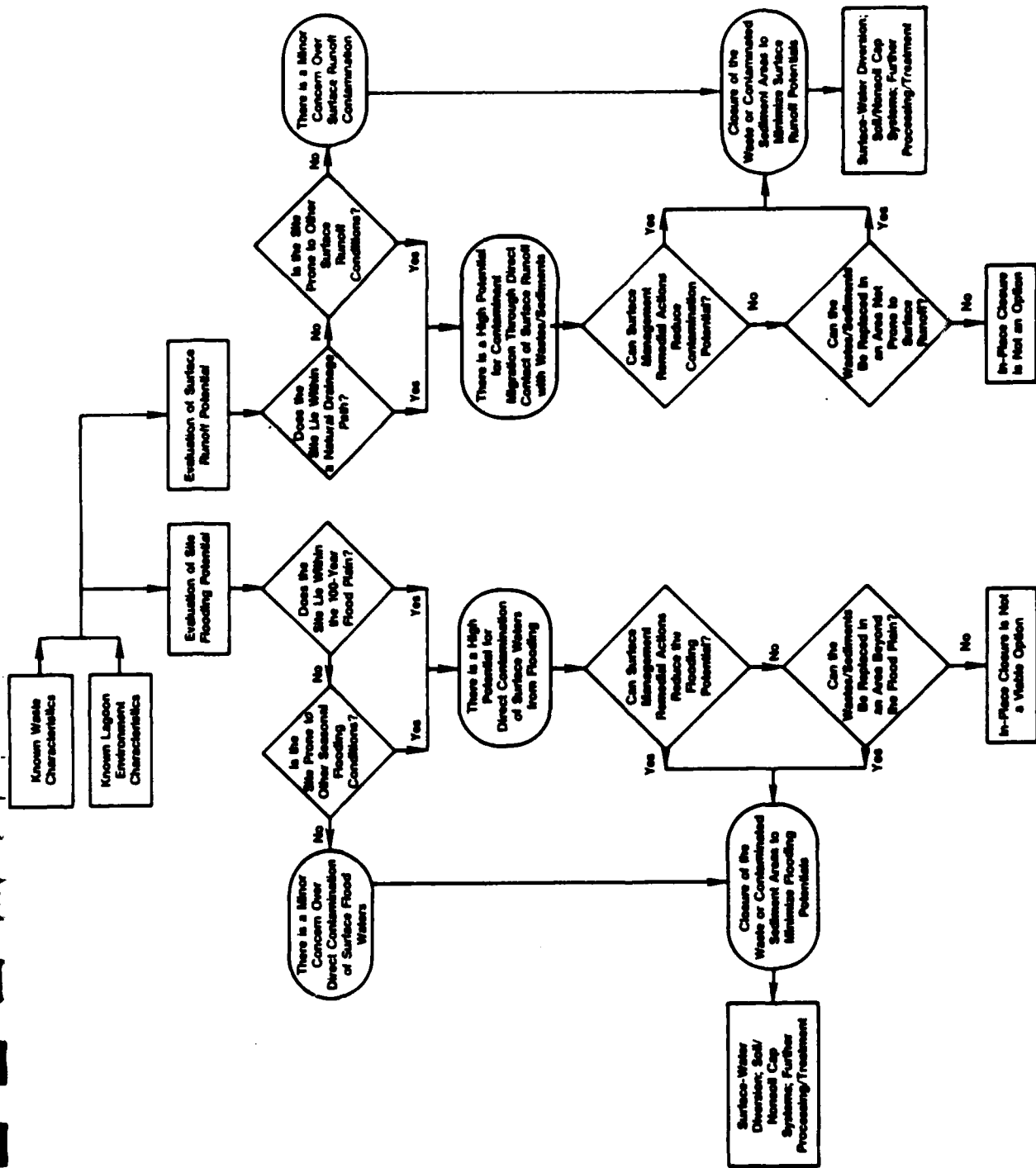
Figure 4. Surface area conditions.

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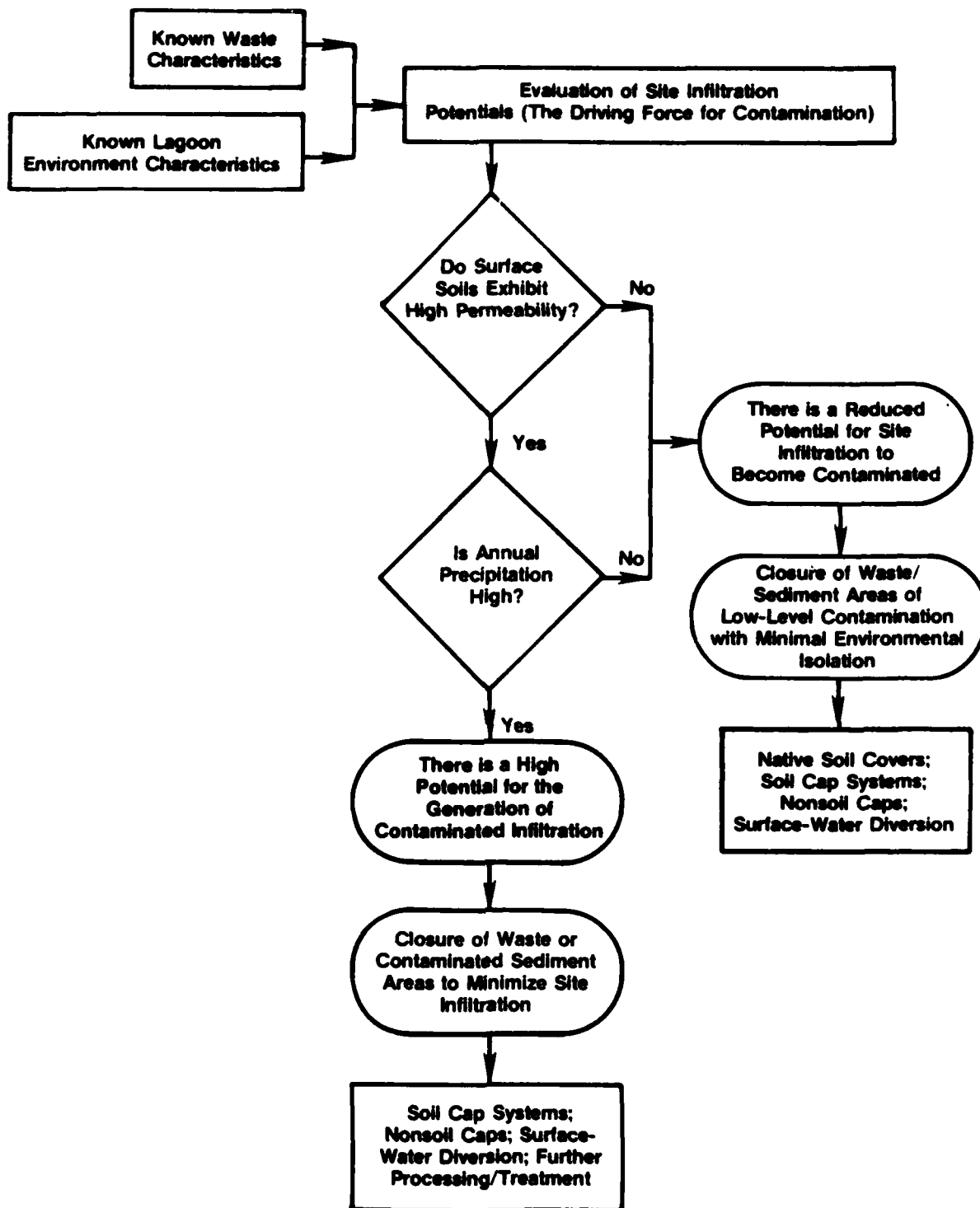
Figure 5. Surface infiltration considerations.

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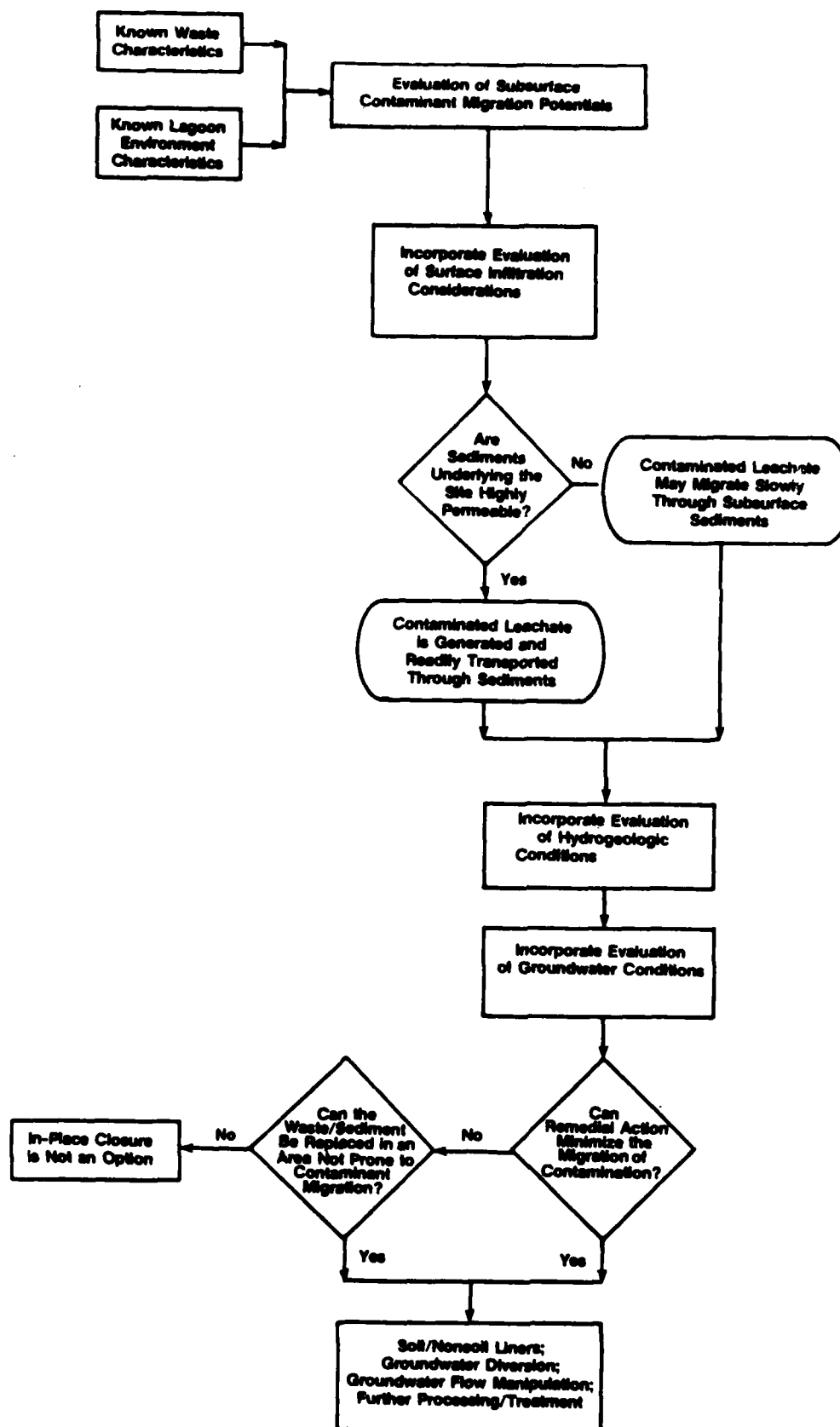
Figure 6. Subsurface soil characteristics.
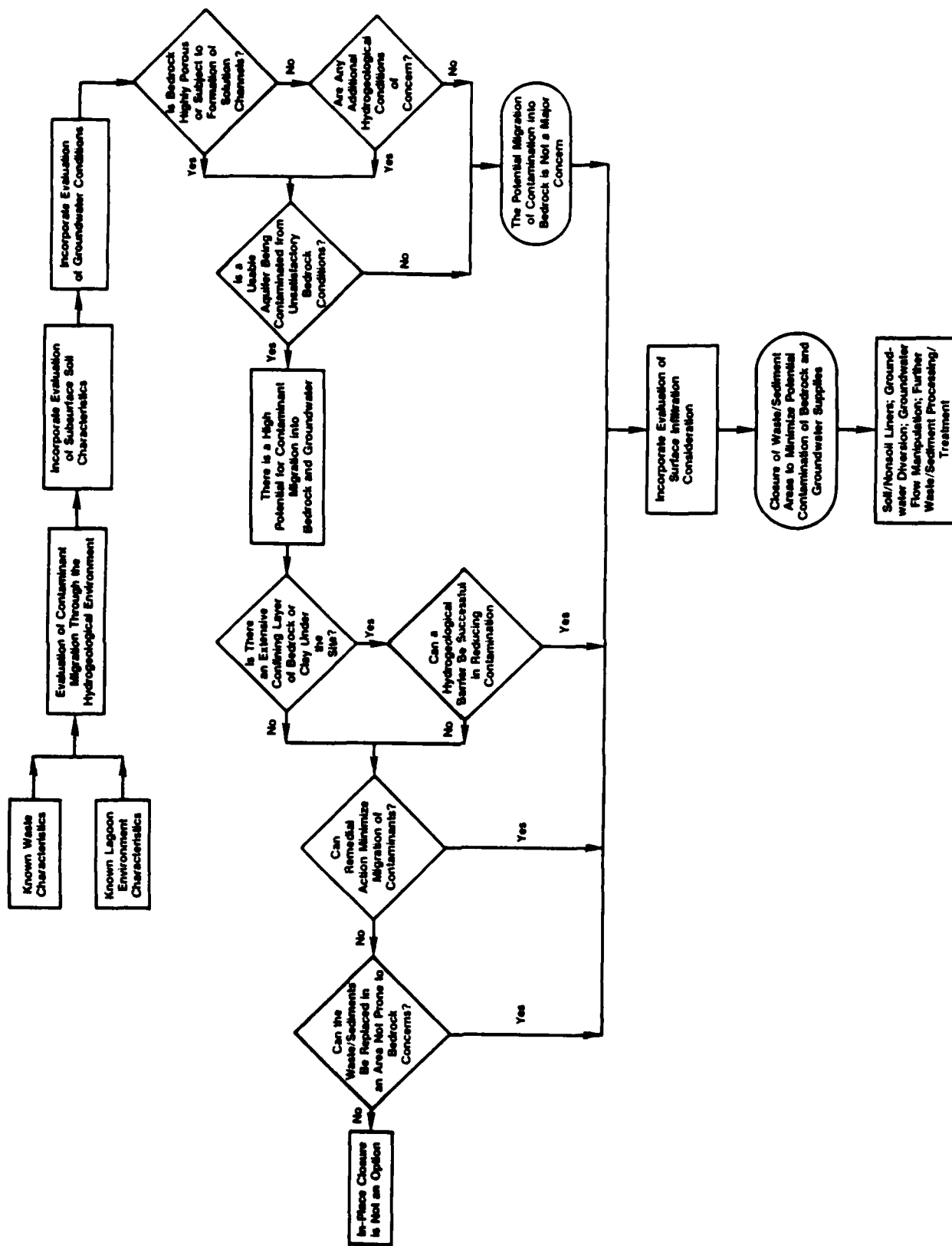
Figure 7. Hydrogeological conditions.

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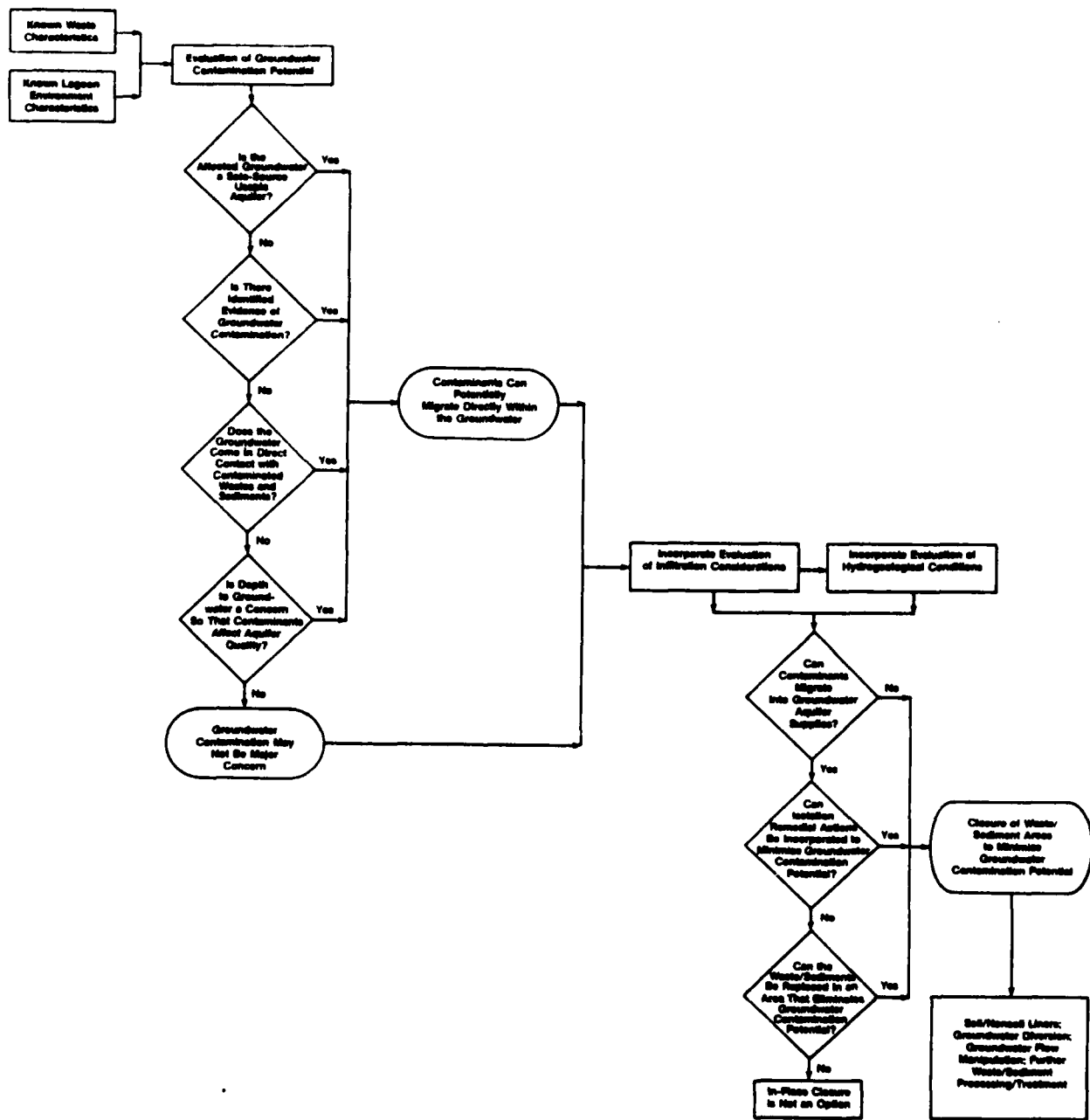
Figure 8.   Groundwater conditions.

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2.2.2.2 Surface-area conditions. The first major contaminant pathway that must be addressed is direct contamination of surface water through either flooding or surface runoff. Figure 4 traces the decision variables that are a part of the evaluation of surface area conditions. The results of the waste and lagoon area characterization evaluation (see Figure 3) comprise the input information to this matrix. Major decision variables involve the evaluation of site flooding potential and the evaluation of surface runoff potential. As the figure indicates, flooding is a concern in in-place closure where the contaminated area lies within the 100-year flood plain or is prone to other seasonal flooding conditions, and where remedial actions or waste removal/replacement is not feasible. In these situations, flooding becomes a limiting constraint and in-place closure may not be an option for remedial action.

Surface runoff contamination is a major concern in other situations where the disposal or highly contaminated site lies within a natural drainage area, or in an area prone to other surface runoff conditions, and where remedial actions or waste removal/replacement is not feasible. As in the similar situation with flooding, the potential for contaminated surface runoff becomes a limiting constraint for the application of in-place closure. If flooding and surface runoff are not of concern r if remedial actions, such as surface runoff diversion, waste excavation, and waste reburial, can mitigate the potential contamination of surface waters, the decision maker should proceed to evaluation of other potential contaminant pathways.

2.2.2.3 Surface infiltration considerations. Figure 5 shows the decision matrix that should be incorporated to evaluate infiltration potential as a contaminant pathway. Site infiltration is a measure of the water that can migrate through the surface soils and potentially come in contact with the waste material. Infiltration can be looked upon as the driving force behind sub-surface contamination, since in most situations, the percolating infiltration can carry the contaminants through the soil. The key decision variables in the evaluation of site infiltration potentials (as shown in Figure 5) include whether or not the surface soils exhibit high permeability rates, and whether or not annual precipitation at the site is high. These are the major environmental characteristics that determine the potential generation of contaminated infiltration. Remedial actions can be incorporated to mitigate surface infiltration potentials. These may include the use of native soil covers (if there is a reduced potential for site infiltration), soil and nonsoil cap systems, surface-water diversion, and processing/treatment techniques to reduce the leachability of the waste.

2.2.2.4 Subsurface soil characteristics. Soil characteristics play a major role in the potential subsurface migration of contaminants at a waste disposal area. Figure 6 presents the decision matrix for the evaluation of subsurface leachate migration as a potential contaminant pathway. This evaluation matrix reflects the complex interrelationship between subsurface soil characteristics, site hydrogeology, and groundwater characteristics. An assessment of subsurface contaminant migration must incorporate key decision variables regarding the subsurface soil characteristics (such as soil permeability) as well as the evaluation results of surface infiltration considerations (see Figure 5), hydrogeological conditions (see Figure 7), and groundwater conditions (see Figure 8). If contaminated leachate is generated and is capable of migrating through the subsurface soils, the key concern is shifted to the potential contamination of groundwater. If remedial actions cannot minimize the migration of contaminants and if the wastes cannot be replaced in an area prone to subsurface contaminant migration, in-place closure of these areas may not be an option. Potential closure remedial actions that can be incorporated include soil and nonsoil liner systems, groundwater diversion techniques, groundwater flow manipulation, and further waste processing/treatment.

2.2.2.5 Hydrogeological conditions. Consideration of the site's hydrogeological characteristics is of major importance to an effective evaluation of potential in-place closure approaches. Figure 7 represents a decision matrix that should be used by the installation commander to assess the impacts of the contaminated areas on bedrock or any other hydrogeological conditions of concern. Key decision variables include whether or not the underlying bedrock is porous or subject to solution channels (such as with limestone Karst topography), whether or not a usable aquifer is being contaminated from hydrogeological conditions of concern, and whether or not an extensive confining layer is underlying the site.

As seen in the discussion of subsurface soil characteristics, the evaluation of hydrogeological conditions must incorporate the results of other contaminant pathway evaluations, which include surface infiltration considerations (see Figure 5), groundwater conditions (see Figure 8), and subsurface soil characteristics (see Figure 6). The use of the appropriate remedial closure techniques is dependent on the specific hydrogeological conditions of concern. If bedrock is highly porous and contaminant migration is prevalent within a bedrock aquifer, and no remedial action can be implemented (including waste removal/replacement), in-place closure would not be an appropriate option.

Some of the remedial actions that may be incorporated include the use of soil or nonsoil liners (to prevent leachate migration), groundwater diversion techniques (to tie into a confining layer and prevent lateral movement of groundwater), groundwater flow manipulation, and further waste or contaminated soil processing/treatment.

2.2.2.6 Groundwater conditions. The contaminant pathway of ultimate concern to an in-place closure strategy is the groundwater flowing beneath the installation. Groundwater location, flow characteristics, and contamination potential represent critical environmental conditions that must be addressed. Figure 8 shows the decision matrix that could be used to evaluate groundwater contamination potentials and to assess the application of potential remedial actions. Some of the key decision variables requiring evaluation include whether or not the affected groundwater supply is a sole-source usable aquifer, whether or not evidence of groundwater contamination exists (indicated by on-post and off-post monitoring of groundwater), whether or not groundwater comes in direct contact with the wastes or contaminated soils (as in the case of seasonally fluctuating groundwater elevations), and whether or not the depth to groundwater are of concern. Incorporation of the evaluation results from the infiltration considerations and hydrogeological conditions is also important, since they affect direct or gradual migration of contaminated leachate into the groundwater. Similar in-place closure techniques can be used to minimize groundwater contamination potential as discussed in reference to hydrogeological control measures.

2.3 Summary of in-place closure technologies. This subsection presents an overview of the remedial action technologies for in-place closure of abandoned lagoons and waste disposal areas. These technologies are described as source control remedial actions since they can be applied at military installations to close out inactive waste sites while addressing the environmental concerns over the potential contamination of soil, groundwater, and surface-water supplies. Each of the potential in-place closure techniques is summarized herein and described in detail in Sections 3 through 8. The basic format incorporated for each technology summary is as follows:

(a) Technology description.
(b) Applicability/uncertainties.
(c) Performance verification.
(d) Economic considerations.

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A brief description of the technology is provided to identify the components of the remedial action as well as the environmental goals of its application. The applicability of each closure technology is assessed in terms of its effectiveness as a source control measure for specific waste types and site characteristics. The success of various closure techniques is dependent on the waste-specific and site-specific characteristics of the application, and a discussion of the limitations of application is important to an evaluation of the remedial actions. Performance verification is included to describe the methods utilized during design and construction of the remedial action to confirm its effectiveness as an in-place closure technique. A discussion of economics is included to provide an overview of the costs to be anticipated for a particular closure technique. Approximate costs are provided as a qualitative benchmark for comparison of various technologies.

2.3.1 Soil cap systems (Section 3). Soil caps are applied as in-place closure techniques to limit the infiltration of precipitation into the waste site, and to provide containment of the contaminated areas. A variety of closure techniques may be incorporated as components of soil cap systems. Their applications vary, depending on the waste characteristics, site conditions, and required closure objectives. The five soil cap system techniques, which are discussed herein, are as follows:

(a) Multilayer cap systems.
(b) Native soil covers.
(c) Soil/bentonite admixtures.
(d) Geotextile fabrics.
(e) Bio-barrier systems.

2.3.1.1 Multilayer cap systems.

Description -- The multilayer cap system represents an engineered solution for in-place closure of a wide variety of abandoned lagoons and contaminated areas. The multilayer cap provides a high degree of containment and infiltration control through the application of three distinct soil layers with separate closure functions. The description and function of each of these layers follows:

(a) Uppersoil layer -- A topsoil and native soil layer, typically placed to a depth of about 12 to 24 inches. This layer serves to support vegetation, provide a cover for the drain layer, and divert surface runoff. Vegetation stabilizes the cover system, protects against water and wind erosion, and contributes to evapotranspiration moisture loss.

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(b)   Middle drain layer -- A graded layer of porous sand or
       gravel material to act as a flow zone and drainage
       medium. This zone of rapid permeability materials is
       typically placed over the cap layer to a depth of
       about 18 inches and enhances the lateral movement of
       percolating water.

(c)   Cap layer -- A compacted layer of fine-grained and low
       permeability soils placed to divert infiltration that
       has percolated through the upper soil layer. The cap
       layer, typically placed to depths of about 18 to 24
       inches, incorporates the use of clays and soil admix-
       tures to provide a surface seal over the contaminated
       area.

Applicability/uncertainties -- The multilayer soil cap sys-
tem presents wide application to in-place closure of abandoned
lagoons and contaminated waste disposal areas. The multifunc-
tional objectives of the three layers, as well as the use of
natural soil materials, promotes successful application to a va-
riety of closure situations. Infiltration of percolating rainwa-
ter into the site can be controlled by appropriate grading,
placement of the soil cap and drain layers, and revegetation.
Designs of multilayer cap systems can be adapted to various
site-specific and waste-specific applications.   Six factors
should be assessed to determine the applicability of multilayer
soil cap systems. These are as follows:

(a)   Native geological considerations.
(b)   Area climatic conditions.
(c)   Chemical and physical waste characteristics.
(d)   Upper soil layer design basis.
(e)   Drain layer design basis.
(f)   Cap layer design basis.

Performance verification -- To ensure the performance of a
multilayer soil cap system as an infiltration control measure,
verification steps should be taken during design and implementa-
tion. Design considerations should include the required thick-
ness of the low permeability cap layer and high permeability
drain layer, the desired slope of the cap system, and the type
of vegetation and surface runoff controls. Implementation con-
siderations include materials selection and testing as well as
construction testing techniques. Materials verification may in-
clude soil classification for selecting appropriate materials,
sieve analysis of representative soil candidates to verify soil
type requirements, and liquid limit and plastic limit analyses

to determine the workability of cap materials. Construction verification usually entails visual inspections of cap materials to ensure suitability, standardized compaction tests to provide maximum soil density at optimum moisture content, and topographical surveys to ensure site work grades are appropriate.

Economic considerations -- Placement of multilayer soil cap systems represents a relatively cost-effective method of accomplishing the desired goals of in-place closure. Imposed costs are well defined, since soil cap systems have widespread application in hazardous waste management. These costs are variable, however, since the local availability of required cap materials is an important cost consideration. In general, the cost range for placement of soil cap systems is approximately $75,000 to $125,000 per acre of cap area. Some of the specific cost factors for multilayer soil cap systems are as follows:

(a) Site preparation, which may include cut-and-fill and rough grading activities, to develop the required site grades at approximately $1 to $2 per cubic yard for excavation, hauling, and placement of soils, and $1.50 to $2.50 per cubic yard for grading site work.

(b) Purchase and delivery of locally available cap layer materials at approximately $3 to $8 per cubic yard of clean fill and topsoil and $5 to $20 per cubic yard for native clays and aggregate stone, with placement costs of $2 to $4 per cubic yard of material.

(c) Revegetation of cap system, including mulch, fertilizer, lime, and seed at approximately $5,000 per acre of area.

2.3.1.2 Native soil covers.

Description -- Native soil covers represent single-layer caps that are spread and compacted over abandoned lagoon areas as part of in-place closure strategies. In climates where evaporation rates are greater than precipitation, in locations where low permeability native soils are readily available, and in situations with minimal contaminant migration potential, the use of a multilayer cap system may not be necessary. In these situations, the placement of a native soil layer may provide the adequate capping requirements.

Applicability/uncertainties -- Single-layer native soil covers simply provide a physical barrier against human contact with the contaminated area and provide a mechanism for improved surface runoff. Beyond the evapotranspiration and surface management controls achieved through regrading, placement of a native soil cover, and revegetation, only slight reductions in the rate of subsurface infiltration are gained. The level of subsurface environmental control achieved through native soil capping is not as great as that of a multilayer cap system.

Native soil covers should only be considered when complete waste isolation is not required and a significant reduction in site infiltration is not a primary concern. In dry climates where evaporation is greater than annual rainfall, the amount of infiltration is generally not a major concern and infiltration controls would only apply on a seasonal or storm event basis. Nonleachable waste areas can be appropriately closed with native soil covers. Subsurface percolation can pass through the insoluble waste, but little or no contaminated leachate would be generated. In the situation where waste processing or solidification is incorporated into a waste containment strategy, native soil covers may be a satisfactory capping approach.

Performance verification -- Designs of native soil covers should consider soil layer thickness and soil type. Cover soil thickness should be adequate to protect the cover integrity from frost damage and should be capable of supporting vegetation. Proper selection of vegetation for shallow root penetration should be a part of the native soil cover design. During the selection of cover materials, consideration should be given to the specific application of the native soil cover. If infiltration reduction is not a primary objective, then the native soil cover will be serving more as a physical barrier over the contaminated area and a medium for vegetative growth. This objective could be met by a clean soil fill material. If infiltration reduction is a primary objective, the native soil cover will more closely resemble a clayey soil material. In both cases a topsoil layer may be recommended to help establish vegetative growth. The same implementation and construction verification techniques would be required for native soil covers as those described for the multilayer soil cap system.

Economic considerations -- Placement of a single layer native soil cover would entail the same basic construction activities as the multilayer soil cap system, and the imposed cost factors would be the same for material purchase, delivery, and placement.

2.3.1.3 Soil/bentonite admixtures.

Description -- A low permeability soil/bentonite admixture represents an appropriate component of an in-place closure or containment strategy. Soil/bentonite admixtures can be placed as the cap layer in the multilayer cap system or as a single layer cover system. These admixtures incorporate a combination of natural and processed bentonite and can replace natural low permeability clay soils, when adequate native soil deposits are not available or cannot be used in a cost-effective manner. Dry powder or pellet bentonite is placed and admixed with the site soils, and the mixture is uniformly spread and compacted. Once hydrated, the bentonite swells to fill the void spaces within the soil layer, and the resulting admixture achieves a high degree of infiltration control.

Applicability/uncertainties -- Bentonite admixtures present a wide application to hazardous waste management where native clay soils are appropriate. Bentonite contains practically the same chemical constituents as other clay substances, but its unique molecular structure accounts for its ability to adsorb many times its own weight in water. Bentonites swell significantly in the process, with increases at full saturation ranging up to 15 times their original dry bulk. This swelling characteristic may create problems in contaminated waste areas. In the presence of certain chemicals, natural bentonites may undergo significant shrinkage characteristics, with adsorbed interstitial water being driven from the expanded soils. This has the net adverse effect of actually increasing the permeability of the admixture. To counteract this physical and chemical phenomenon, processed bentonites have been marketed with certain additives to reduce the potential for chemical attack for soil/bentonite applications with contaminated wastes.

Performance verification -- Design verification as well as construction verification techniques represent important components of evaluating the effectiveness of soil/bentonite admixtures. Selection of the bentonite admixture should include an evaluation of waste characteristics and materials compatibility, site-specific geotechnical characteristics, and required bentonite application rates. When looking at compatibility, consideration should be given to selection of either native bentonites or contaminant-resistant bentonites (for hazardous waste applications). Geotechnical assessments should include performance of standardized soil testing methods, such as soil type, porosity and void ratio, soil graduation and pore size distribution, moisture content, and Atterberg indices. Bentonite application

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rates are dependent on the admixing soil types and the degree of desired infiltration control. Admixture designs are generally referenced in pounds of bentonite applied per square foot of soil (typically 2 to 10 pounds per square foot), and verification typically entails materials quantity estimates and mixture depths (depth range of 6 to 24 inches). Bench-scale tests should be performed to verify application rates and confirm compatibility issues.

Verification of bentonite admixture placement generally involves construction techniques used in earthmoving activities and roadbed construction. Subgrade soil preparation must be performed and a decision about the bentonite placement method should be made. Soil/bentonite admixing may be accomplished through either manual or mechanical methods. Manual placement and admixing procedures were utilized during the early soil/bentonite applications. As construction techniques have expanded, mechanical spreading and discing techniques have been incorporated to enhance process control. The greatest level of quality control can be achieved through bulk admixing of the soil and bentonite in a pugmill or equivalent equipment type, and mechanical placement of the admixture layer using an asphalt paver or equivalent equipment type.

Economic considerations -- Bentonite admixtures are typically used in place of native soils as an impermeable cap material. While they provide a more homogenous and lower permeability cap layer than ordinary clay materials, the costs of bentonite admixtures are typically higher, unless native clays are not locally available. Clean till (usually silty sands) are admixed with imported bentonite. Powdered bentonite purchase and delivery costs are typically $225 to $275 per ton, with bentonite application rates ranging between 4 and 10 pounds of bentonite per square foot of capping surface. Including material purchase and delivery, as well as admixing and placement activities, the cost of a bentonite/soil admixture as an impermeable layer is typically approximately $90,000 to $110,000 per acre of cap area.

2.3.1.4 Geotextile fabrics.

Description -- Synthetic fabrics have been used in construction for reinforcement, separation of materials, erosion control systems, and flexible forms. These construction applications place specific emphasis on improvement of subgrade conditions common to heavy construction and geotechnical engineering problems. Geotextile fabrics incorporate synthetic materials (typically nylon, polyester, and polypropylene) in the production of either woven or nonwoven mats.

Applicability/uncertainties -- Various fabrics are currently available for application in many in-place closure situations. Each exhibits varying physical, mechanical, and hydraulic properties, as well as the characteristics of endurance and waste compatibility. Geotextile fabrics are rapidly becoming commonplace in the construction industry. The number and type of appropriate applications are continually expanding because of rising labor costs and increasing problems with locally available soil materials. Construction geotextile fabrics may be applied to serve the following basic functions for a waste containment strategy:

    (a)   Separation.
    (b)   Reinforcement.
    (c)   Drainage.
    (d)   Erosion control.

Separation geotextile fabrics can be placed between dissimilar soil material layers to reduce the effects of settlement, frost action, and roadbed deterioration, and may enhance subgrade soil permeability and strength characteristics. Reinforcing geotextiles have been used successfully in situations of poor to marginal soil stability characteristics, and can be applied to enhance the load-bearing capacity of soil subgrades.

Drainage geotextile fabrics can be installed to replace sand or gravel flow zone layers and enhance in-place permeability (as in a multilayer cap system), and may be used in place of soil filters to prevent the migration of soil fines and the clogging of drain layers. Construction geotextiles may also be placed to control surface and subsurface soil erosion, since they can be placed beneath a stone layer, gabion blanket, or riprap layer to protect embankment side slopes. The predominant uncertainty with geotextile fabrics lies in the assessment of a particular fabric material for a specific geotechnical application. Strength characteristics and waste compatibility considerations may prohibit geotextile applications in certain situations.

Performance verification -- The first step in performance verification lies in the assessment of site-specific geotechnical conditions and potential fabric applications to match the appropriate fabric with its design application. Design methodologies are available to evaluate subgrade stability (calculation of radial stress for load-bearing stability improvements), subgrade drainage applications, and erosion control applications.

Laboratory testing results are typically used to verify the performance of geotextile fabrics for specific properties. Some of these laboratory testing procedures are as follows:

(a) Weight (physical property).
(b) Thickness (physical).
(c) Compressibility (physical).
(d) Tensile strength (mechanical property).
(e) Elongation (mechanical).
(f) Creep behavior (mechanical).
(g) Abrasion resistance (mechanical).
(h) Porosity (hydraulic property).
(i) Water permeability (hydraulic).
(j) Planar water flow (hydraulic).
(k) Soil retention/piping resistance (hydraulic).
(l) Chemical resistance (endurance property).
(m) Weather/ultraviolet resistance (endurance).
(n) Temperature resistance (endurance).
(o) Burial deterioration (endurance).

The final performance verification steps consist of construction and fabric placement approaches. Subgrade stability steps, such as surface rolling, compaction, and removal of debris, must precede placement of the geotextile. Placement of the fabric can be accomplished manually or by mechanical rollers. Most fabric applications do not require seaming techniques, and overlapping adjacent fabrics may be sufficient. In some stability improvement applications, however, tensile strength is of critical concern and sewn seams are necessary. In these cases, seam strength tests should be applied to ensure adequate seam performance.

Economic considerations -- Geotextile fabrics are not expensive and represent a cost-effective addition to a multilayer cap system or for use in other in-place closure actions. Fabrics of various materials, weights, and thicknesses are available at approximately the same unit costs. These costs run typically between $0.08 and $0.20 per square feet of fabric for purchase, and between $0.03 and $0.06 per square foot for placement and seaming techniques. In many applications, use of geotextiles may actually preclude the use of more expensive fill and aggregate materials.

2.3.1.5 Bio-barrier systems.

Description -- Bio-barrier systems represent an emerging technology for the control of plant root growth and burrowing animals. One concern regarding the long-term integrity of cap systems for use under an in-place containment strategy is the potential intrusion of plant roots and burrowing animals into the cover soils. The useful life of cap materials may be subject to a number of physical, chemical, and biological factors. Plant and animal breaching of the cap materials may lead to increased infiltration and a decline in the overall efficiency of the cap system for minimizing infiltration. Furthermore, burrowing animals in western states have been known to excavate large areas for habitation in soft clay soils, and may carry waste materials to the surface of the site. Physical and chemical bio-barrier systems have been studied for application in waste containment, specifically in the long-term containment of uranium mill tailings.

Applicability/uncertainties -- Development of bio-barriers has not reached the wide-scale implementation stage at present, but laboratory test results indicate favorable potential applications in waste management. Some laboratory and field experience has been gained in the use of stable polymeric carrier/delivery systems (PCD) to limit the potential intrusion of plant roots. A PCD system should be designed to release the biocide into the soil for an extended period of time, select a biocide that is compatible with the vegetative cover, and maintain appropriate biocide concentrations to limit root growth only in the prescribed soil zones. In addition to root biocides other bio-barrier systems are currently under investigation. Potential bio-barriers may include, but not be limited to, the following materials:

(a) Crushed rock or aggregate layers.
(b) Asphalt emulsion layers.
(c) Multilayer combinations of pea gravel, rock clay mix, sand, or asphalt emulsion.
(d) Geotextile fabrics, reinforced fabrics, geotextile mesh.

Performance verification -- Since the use of bio-barrier systems has not reached widespread application, no emphasis to date has been placed on performance verification. Laboratory work is addressing predominantly time-controlled release herbicides and inert animal intrusion control measures.

Economic considerations -- No information is available to date regarding application costs for bio-barrier systems. Maintenance costs, however, should be minimal since these controls are passive in nature (requiring no monitoring or upkeep) and represent one-time expenditures during the construction of the cap system.

2.3.2 Nonsoil caps and liners (Section 4). In-place closure and containment may be achieved through the use of impermeable nonsoil caps and liners. Surface caps may be used to contain waste materials and reduce the potential for leachate generation, while impermeable liners may be used as a boundary to contain wastes and stop the migration of pollutants into the subsurface soils. This subsection outlines the two basic technologies available for use as nonsoil caps and liners, i.e., asphalt/concrete materials and synthetic polymer membranes.

2.3.2.1 Synthetic polymer membranes.

Description -- Flexible synthetic membranes represent an effective overall technology for the containment of abandoned waste lagoons because they can provide an infiltration control boundary of very low permeability. These synthetic membranes are products of the plastics and rubber industries. The polymeric materials used in the manufacture of these covers and liners include vulcanizable and nonvulcanizable thermoplastics, plastics, and rubbers. They are all synthetic materials, varying from highly polar polymers, such as polyvinyl chloride (PVC), to nonpolar polymers, such as EPDM and butyl. They range from amorphous polymers, such as the rubbers, to crystalline polymers, such as polyethylene. Generally, polymeric materials are compounded with fillers, antidegradants, plasticizers, and curatives if vulcanization is needed. Compounds based on the same polymer can vary considerably in composition from manufacturer to manufacturer, depending on the grade and the price of the material.

Applicability/uncertainties -- Synthetic membranes can be used as the impermeable cap within a multilayer cover system, or can form the basis of an impermeable liner at the base of a waste lagoon or landfill disposal area. Their applications are wide and varied, however, in general, synthetic covers and liners are susceptible to the same types of long-term failure mechanisms as asphalts and concrete. In addition, synthetic membranes are prone to punctures due to root penetration and damage during placement. Severe puncture damage can result in the escape of pollutants, and surface-water infiltration. Synthetic

membranes are also prone to microbial attack, which, in the context of a permanent closure plan, becomes a significant consideration.

Performance verification -- Careful evaluation of the proposed application for a synthetic polymer membrane should represent the initial aspect of performance verification. Selection of candidate material types and thicknesses should be based on a detailed knowledge of the waste characteristics to be contained, as well as the purpose of the application. Some of these design considerations are as follows:

(a) Compatibility witn lagoon wastes and volatiles/gases produced.
(b) Ability to impede percolation (cap) or contain leachate (liner).
(c) Crack resistance.
(d) Resistance to biological degradation.
(e) Ease of construction.
(f) Seaming and seam integrity inspection techniques.

Once a material has been selected, performance verification is shifted to construction and post-closure monitoring, where the key objective is leak detection. During construction, nondestructive and destructive tests for tensile stress can be applied to verify seam integrity. In addition standardized earth-moving techniques such as visual inspections and compaction tests should be applied to ensure subgrade stability prior to placement of the cap or liner material. Leak detection after closure has been classically accomplished through groundwater monitoring of contaminant concentrations. Elevated downgradient groundwater contamination reflects the presence of a liner leak, but the hazardous materials must reach the groundwater at the monitoring well.

At present, there are no proven methods that can determine the source of a leak in a liner material before contaminants reach the groundwater. Various innovative and emerging technologies are now being developed to assess the long-term effectiveness of impermeable boundaries, such as synthetic polymer membranes. It should be noted that these techniques have not been applied at existing land disposal areas, but research activities indicate good promise for future application. Two general approaches to leak detection are being addressed: construction of a subliner monitoring system during placement of the landfill and post-closure leak detection techniques. One such subliner technique includes the direct current (dc) grid system, where

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electrical wires are laid in a cross-grid pattern under the liners, and corroded wires (broken dc circuit) detect liner failures and leaks. The other subliner technique, time-domain reflectometry (TDR), incorporates wide frequency electrical transmissions along a parallel-grid of wires beneath the liner. Liquids and leak materials from waste impoundments will exhibit different electrical properties than the native soils, and TDR techniques will detect any electrical property variations.

Leak detection after closure of existing impoundments and lagoons requires a different type of performance verification technique, one which would be incorporated from a location beyond the lagoon. One such method, the neutron soil-moisture meter, can be used to detect increases in soil moisture content (i.e., liner or cap system leaks) through the emission and detection of high energy neutrons. These neutrons are scattered through the soil, and the density of detected neutrons (recorded in counts per unit time) reflects any changes in soil moisture content and the extent of the leak. Another post-closure technique being investigated includes acoustic emissions monitoring (AEM), which is a well-established technique for evaluating stresses in rocks and metals and for measuring turbulent flow through earth dams. Microphones can be placed in adjacent soils, and the acoustic emissions of water moving through the soils can be detected, locating the liner failure and potential leak. The final post-closure leak detection technique incorporates basic electrical theory of voltage, current flow, and plotting of equipotential lines. The liner is approached as an electrical insulator, and current is provided to the liquid waste impoundment. The current flow is traced, and where a leak exists, the current flow pattern is altered along the leak path. Through selection of multiple starting points above the lagoon and computer plotting of the resulting equipotential lines, triangulation upon the actual leak location is possible. Once leaks are identified, no practical solutions to liner retrofitting are available, and the current solutions involve waste removal, treatment, reburial, or offsite disposal.

Economic considerations -- Polymer membranes are available in various materials and thicknesses, and costs are variable, depending on the design applications. The following represents a list of synthetic membrane costs for liners and caps, including purchase and installation:

(a)   PVC (20 mil thickness) at $1 to $2 per square yard.
(b)   Chlorinated PE (20 mil) at $2 to $3 per square yard.
(c)   Elasticized polyolefin at $3 to $4 per square yard.

(d) Hypalon (30 mil) at $7 per square yard.
(e) Neoprene at $5 per square yard.
(f) Ethylene propylene rubber at $3 to $4 per square yard.
(g) Butyl rubber at $3 to $4 per square yard.

2.3.2.2 Asphalt/concrete materials.

Description -- Solidified caps and liners may incorporate the use of asphalt emulsions, asphaltic concretes, and concrete mixes for impermeable layers as part of a waste containment strategy. Asphalt emulsions can be used to construct caps and liners by spraying a prepared soil surface with liquid asphalt, which then solidifies to form a continuous, low permeability membrane. Asphaltic concretes are also available as waterproofing and caulking agents, and can be applied to form watertight layers. Concrete mixtures can be applied as a solid cover material, but inherent discontinuities make it difficult to create an impermeable layer.

Applicability/uncertainties -- While asphalts and concretes have been used successfully to provide a seepage barrier and for waterproofing, widespread application to hazardous waste management is not recommended. Care must be taken in the selection of an appropriate application. Recent use of asphalt materials for containment has shown that while asphalt is resistant to weak acids, bases, inorganic salts, and corrosive gases, they generally are not resistant to organic solvents. Sun aging, creep tendencies, and subgrade movements may also reduce the effectiveness of asphalt covers and liners. Asphalt concrete cover and liner systems may be subject to penetration by weeds, since the concrete discontinuities can serve as a growing medium. Concrete exhibits other concerns when used alone in hazardous waste applications. Concrete cannot be placed in the field to provide an impermeable boundary, since required construction joints present leakage problems. In addition, concrete is susceptible to cracking, and subgrade stability is a major concern.

Performance verification -- It is difficult to ensure the performance of solid caps as impermeable layers. A good understanding of waste and site-specific characteristics is a key element in the design of these systems. During construction, it is difficult to ensure complete cover through asphalt spraying due to small protuberances that receive only partial cover. Sprayed-on liners and caps can be placed seam free, but constructing them "pinhole" free poses serious problems in the field. During placement of asphaltic concrete layers, it is difficult to control parameters such as mixing temperatures, spreading time, time laps between spreading and compaction efforts, and compacting effectiveness.

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Economic considerations -- Solid caps are relatively expensive to purchase and place. Some typical costs for the potential application of asphalt and concrete covers follows:

(a) Cement concrete (mixed, spread, and compacted for a 4- to 6-inch layer) at $6 to $10 per square yard.

(b) Asphaltic concrete (4- to 6-inch layer) at $3 to $5 per square yard.

(c) Sprayed asphalt membrane (1/4-inch layer, including solid cover) at $2 to $3 per square yard.

2.3.3 Surface-water management (Section 5). Surface-water management techniques may be applied to in-situ lagoon closure plans to help provide long-term stability at a closure site. Surface-water diversion is rarely, if ever, the only remedial measure taken at a lagoon site. Normally, surface-water control is used in conjunction with other remedial measures such as surface sealing, groundwater management, and/or waste treatment, in an integrated closure plan. The primary objective of diversion is to hydrologically isolate a closed lagoon from surface-water inputs, and thereby reduce the potential for leachate generation and damage to other engineering control measures such as erosion of cover materials.

2.3.3.1 Surface grading/diversions.

Description -- Grading is a broad term used to describe techniques commonly used in the construction industry to reshape existing land surfaces. Grading can be used during site closure as a surface-water runoff and erosion control measure. Excavation, hauling, spreading, and soil compaction are the major elements of a complete grading operation. Heavy construction equipment is required for these operations. Surface diversions are drainageways that are constructed along the contours of graded slopes to intercept and convey runoff away from the disposal area.

Applicability/uncertainties -- Surface grading and diversion structures can be applied as part of any in-place closure/containment strategy. The overall objectives of grading are applicable to any abandoned waste lagoon area. These include the control of surface runoff while minimizing soil erosion, and the use of diversion ditches to control the movement of collected runoff at nonerosive velocities. In some applications where disposal lagoons are at low-lying elevations, grading and surface diversion techniques are incorporated to direct surface water away from higher elevated surrounding areas (i.e., diversion of runon).

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Surface-water management technologies should be designed on a site-specific basis considering local environmental conditions and potential land use considerations. The surface management measures must be compatible with the other engineering control techniques to be implemented under the remedial action program. The following factors should be considered when assessing the potential application of surface-water management:

(a) Final site topography and grading plan.
(b) Overall drainage plan for the site and surrounding area.
(c) Final cover system.
(d) Site access.
(e) Final site use.

Performance verification -- Environmental performance verification of surface-water diversion structures consists primarily of the following measures:

(a) Quality control/construction management.
(b) Post-construction inspections.

Quality control/construction management is necessary to ensure that all design specifications are met during construction of diversion structures. Typical elements of a quality control program include site surveying, soil testing, and visual inspections. All surfaces should be checked for proper compaction and accurate grade levels. Cement and asphalt, if used, must be poured/constructed according to design specifications. Subgrades must be inspected for stability, and all construction materials must be checked to ensure that they conform to design specifications. Post-construction inspection of surface-water diversion structures consists primarily of periodic visual inspections. Any cracks, erosion damage, or malfunctions should be noted and corrected. Periodic maintenance should be performed as necessary.

Economic considerations -- To evaluate the potential costs of implementing surface-water controls, material quantity estimates must be made for soil excavation, grading work, and soil purchase quantities. In general, the following range of unit costs may apply:

(a) Onsite excavation, hauling, placement, and compaction of soils at $1.00 to $2.00 per cubic yard.
(b) Grading site work at $1.50 to $2.50 per cubic yard.

(c) Purchase and delivery of clean fill, aggregate material, or topsoil (variable costs due to material type and local availability) at $3.00 to $10.00 per cubic yard.

2.3.4 Environmental isolation techniques (Section 6). Environmental isolation techniques represent in-place closure measures that are directed toward the passive control of groundwater so as to isolate a lagoon or disposal area from the subsurface environment. As passive control measures, groundwater diversion techniques present little or no long-term operating requirements. Once in place, these controls will continue to function with minimal or no operating support such as utilities or personnel. The technology summaries herein describe two basic approaches to groundwater diversion. These include:

(a) Groundwater cutoff walls.
(b) Grouting techniques.

2.3.4.1 Groundwater cutoff walls.

Description -- The use of groundwater cutoff walls includes slurry walls and sheet piling isolation techniques. These cutoff walls are generally applied as vertical control measures to provide a groundwater flow barrier around abandoned waste lagoons or disposal areas. In general, placement of slurry walls involves either excavating a narrow trench (usually over 3 feet wide) or driving a vibrating beam through a pervious soil deposit and connecting into an underlying low permeability zone. Shallow trenches are normally excavated with backhoe equipment, while for deeper trenches, excavation is performed by clam shell or other large backhoe equipment. The excavated trench is immediately backfilled with a bentonite slurry to support the side walls and provide a low permeability zone. Vibrating beam cutoff walls are normally constructed using modified pile-driving equipment with specialized slurry spray nozzles to fill the soil voids during removal of the beam.

Sheet piling may be considered a method for groundwater diversion. The construction involves physically driving rigid sheets of steel or concrete into the ground to form a barrier to groundwater movement. Typically, these sheets are interlocked or sealed and then driven into the subsurface soils.

Applicability/uncertainties -- Successful applications of cutoff walls require a detailed evaluation of site-specific hydrogeological conditions. For most applications, cutoff walls

must be connected (keyed) to a low permeability stratum (aquiclude) or a competent geological member (bedrock) in order to provide effective groundwater diversion. In these situations, complete isolation of the waste area may be accomplished and continued groundwater contamination can be eliminated. In some cases, however, nonkeyed (hanging) diversion walls may be effective where collection and recovery of lower density fluids (hydrocarbons and petroleum products) are the predominant groundwater concerns.

Slurry walls are rarely the sole remedial action applied during in-place closure of abandoned lagoons, but rather they are usually accompanied by other measures, such as site capping, groundwater management, waste treatment, or waste removal. Slurry wall construction utilizes well-established and commercially available equipment, and slurry walls (trench method and vibrating beam) have been applied successfully at many industrial waste disposal sites.

Sheet piling may be applied as a groundwater diversion technique, although sheet piling walls will generally not form an immediate boundary to groundwater flow. The interlock seams between sheets are not watertight, and a period of time is necessary to allow fine soil particles to clog these interlocks. In some applications with sandy soils, grouting may be required to form a proper seal between adjacent sheets.

Performance verification -- Design of the cutoff wall to match the particular containment application will represent an important performance verification step. An assessment should be made of waste characteristics to determine wall compatibility with the wastes. For instance, bentonite slurries are not compatible with strong organic and inorganic acids and bases, and the presence of highly concentrated electrolytes, such as sodium, calcium, and heavy metals, may lead to significant increases in permeability. Similar compatibility considerations should be given to sheet piling applications, where galvanized, coded, or other special alloy sheets can be applied.

Performance verification during construction of cutoff walls would include a detailed quality assurance/quality control (QA/QC) program at the site. During the construction of slurry walls, QA/QC considerations would include the following:

(a) Materials quality control, such as water quality, bentonite type, slurry quality, etc.

(b) Filtrate loss test, which simulates the formation of a filter cake on the inner walls of the trench.

(c) Slurry viscosity using a marsh cone apparatus, which measures a series of interrelated properties including density, viscosity, and shear strength.

(d) Slurry density should be tested to ensure that the trench slurry is slightly heavier than groundwater.

(e) Excavation tolerances should be verified, such as minimum trench width and depth as well as wall plumbness.

(f) Backfill material should be free of incompatible materials (organics, debris, salts), and should exhibit an adequate particle size distribution.

(g) Permeability is the key to slurry wall performance, and standardized laboratory permeability tests should be performed to verify its effectiveness.

(h) Verification of excavation depth to ensure appropriate connection or keying into the aquiclude.

The main concern in the application of cutoff walls as an environmental isolation technique is the long-term stability and longevity of the remedial action. Post-closure verification factors are described as follows:

(a) Basil stability -- Determination of horizontal movement in the slurry wall or the ground behind the wall (measured by an inclinometer or using optical surveys).

(b) Subsurface settlement -- Determination of the vertical movement of the wall using single point or multiple point gauges.

(c) Groundwater considerations -- Monitoring wells and piezometers may be placed on both sides of the wall to determine groundwater levels (relative hydraulic head drop across the wall) and groundwater quality (effectiveness of the wall in containing and attenuating contaminants).

Economic considerations -- The capital costs of slurry walls and sheet piling walls vary significantly, based on factors such as depth of the wall, hydrogeological conditions, and slurry type. Some of the imposed cost factors are as follows:

(a) Soil/bentonite slurry walls placed in soft soils (3-foot width).

- Up to 30 foot depth $3 to $6 per square foot ($27 to $54 per cubic yard)

                - 30 to 50 foot depth $7 to $10 per square foot
                                         ($63 to $90 per cubic yard)

                - 75 to 125 foot depth $8 to $15 per square foot
                                         ($72 to $135 per cubic yard)

    (b)   When compared to soft soil excavation, placement of
           slurry walls in hard soils increases the unit cost
           by a factor of 2, placement in bedrock usually in-
           creases the cost by a factor of 3 to 5, and using ce-
           ment/bentonite slurries instead of soil/bentonite in-
           creases the cost by a factor of 4.
    (c)   Sheet piling cutoff walls present costs that are not as
           dependent on depth (weight of 5-gauge galvanized
           steel is approximately 11.6 pounds/square foot).

                - Materials $6 to $8 per square foot ($1,035 to
                                  $1,380 per ton)

                - Installation $1 to $3 per square foot ($170 to $520
                                  per ton)

    2.3.4.2 Grouting techniques.

    Description -- Grouting techniques may be applied at an
abandoned waste lagoon to provide a lateral isolation (similar
to cutoff walls) or complete site isolation (directional grout-
ing as a bottom sealing approach). Grouting is a process by
which a fluid of thixotrophic material is injected into earth
material to penetrate and gel or set in place. This results in a
lower permeability of the grouted area as compared to the ad-
joining earth material. These techniques have been used for many
years in the geotechnical field to aid in dam and tunnel con-
struction. Generally, grouting material can be classified in the
following manner:

    (a)   Suspension grouts, which contain fine colloidal materi-
           als such as bentonite, portland cement, or a mixture
           of both in a suspension of water.
    (b)   Chemical grouts, which consist of Newtonian fluids such
           as silicate-base material, organic polymers, bitu-
           mens, etc.

    Applicability/uncertainties -- While grouting is an estab-
lished technique for waterproofing and construction of impermea-
ble boundaries, it has not gained widespread acceptance and
application as an environmental isolation technique at hazardous

waste sites. Application of injection grouting as a means of isolation of contaminated lagoon contents may be limited, due to the following reasons:

(a) Grouting costs can be significantly greater than slurry wall costs.
(b) The same compatibility concerns affect bentonite grouts as those discussed for slurry walls.
(c) It is difficult to ensure wall continuity during construction.
(d) Emerging bottom sealing techniques (block displacement and directional grouting methods) have not proven effective in field applications.

Performance verification -- Very little information is available on chemical compatibility of grouting materials with various contaminants from existing lagoons at Army installations. Procedures for testing grout compatibility and performance assessment have not been developed, and no data are available on the long-term stability and effectiveness of grouting for waste isolation and contaminant migration control. Long-term groundwater monitoring can be used to determine the effectiveness of grout curtains as containment structures.

Economic considerations -- The capital costs of grouting represent perhaps the most significant drawback to potential application at waste disposal sites. In most cases, substantial equipment mobilization costs and hydrogeological pregrouting tests are required. The grouting cost itself is significantly greater than the costs for other environmental isolation techniques. Typical injection grouting costs may range from approximately $125 to $150 per cubic yard.

2.3.5 Groundwater flow manipulation.

Description -- In many in-place closure situations, the control of groundwater beneath the site is of crucial concern, and various groundwater flow manipulation techniques are available as methods of environmental isolation. Through groundwater flow manipulation or pumping strategies, the location and path of the water table can be altered or the contaminated groundwater plume can be captured. There are essentially two ways to achieve flow alteration. One method is groundwater extraction, whereby a "cone of depression" is created in the zone of saturation. Extraction techniques can be incorporated to hydraulically alter groundwater flow patterns or to contain or capture contaminated plumes. The second principal method for active groundwater flow

manipulation is through injection, whereby a groundwater mound is created. Injection techniques can be used to provide reversed or lower hydraulic gradients to isolate the site or as a part of a groundwater extraction/treatment/injection program.

Applicability/uncertainties -- Groundwater pumping strategies represent applicable techniques for the active manipulation of flow patterns for many hydrogeological site conditions. Proper placement of extraction wells in close proximity can create a depression network in which the combined cones of depression lower the effective elevation of the groundwater. In other applications, extraction wells can be incorporated with injection wells or recharge basins to effectively capture and contain contaminated groundwater plumes. Specific applications may include the following:

(a) Lower the water table to prevent direct contact of the groundwater with waste material.
(b) Lower the water table to prevent leaky aquifers from contaminating other water-bearing areas.
(c) Lower an unconfined aquifer to prevent groundwater discharge to a hydraulically-connected receiving stream.
(d) Extraction and injection wells to allow controlled pumping and treatment of the contaminated groundwater, and recharge of treated groundwater to restabilize aquifer flow characteristics.
(e) Extraction wells coupled with passive groundwater controls to allow a more selective pumping of contaminant plumes.

Performance verification -- To ensure the effectiveness of groundwater flow manipulation techniques, hydrogeological investigations should be conducted, and predictive laboratory and field analytical methods should be utilized. Specific environmental parameters, such as hydraulic conductivity, soil porosity, aquifer transmissivity, and aquifer storativity must be established during the design phase to verify the performance of groundwater pumping strategies. The typical verification procedure includes the acquisition of representative soil samples for laboratory analysis and the subsequent field placement of exploratory piezometers and well points for pumping tests. The course of events typically incorporated during the initial exploration of an aquifer includes the following:

(a) Drilling of a test well with one or more observation piezometers to establish general aquifer characteristics.

(b)   Short-term pumping tests to determine empirically the hydrogeological aquifer parameters.

(c)   Application of the appropriate predictive equations using the results of the pumping tests to design the extraction/injection well system required to perform groundwater flow manipulation.

(d)   Long-term monitoring of contaminant trends and flow conditions.

Economic considerations -- Costs for groundwater pumping strategies will vary widely depending on site conditions and pumping requirements. The following unit costs can be applied for comparison purposes in evaluating potential groundwater flow manipulation techniques.

(a)   Header pipe installation around the periphery of the pumping areas at $35 per linear foot.

(b)   Extraction well points to be placed at specified intervals around the periphery of the pumping areas, and connected by the header pipe to the suction pump at $20 to $35 per foot depth for installation, $10 to $20 per well point for fittings, and $200 to $400 for the centrifugal pumps.

(c)   Installation of high capacity extraction wells (typically 6-inch diameter) to induce a composite cone of depression under the site at $2 to $3 per inch diameter per foot depth for installation, $4 to $8 per foot depth for PVC well casing, and $1,000 to $3,000 for submersible 4-inch diameter pumps.

(d)   Installation of monitoring wells (typically 4-inch diameter) to verify the performance of the pumping scheme at the same unit costs cited for purchase and installation of PVC well casings.

2.3.6 In-situ processing/treatment techniques. The in-situ processing and treatment technologies represent methods to directly address lagoon contents, as opposed to slurry walls or cover/cap systems that indirectly address contamination through isolation or containment of the lagoon contents. Treatment techniques may incorporate biological, chemical, or physical processes used to detoxify the wastes or solidify/ stabilize the materials. Treatment and processing technologies for use at military installations must be capable of treating highly complex waste streams. Some of the contaminants of concern include explosives (i.e., TNT, RDX, DNT, nitrocellulose, etc.), solvents (trichloroethylene, dichloroethylene, etc.), and heavy metals.

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The two general technologies described herein for treatment/processing of these waste streams include the following:

(a) Solidification/stabilization.
(b) Biological, chemical, and physical treatment.

2.3.6.1 Solidification/stabilization.

Description -- Waste fixation is a term that is generally used to refer to the solidification/stabilization processes. These processes are normally used to isolate, immobilize, or contain sludge and semi-solid waste materials by combining a fixation agent (admixture material) with the waste. Fixation technologies usually include treatment techniques designed to process the sludge and semi-solid wastes into a solid form. Often this solid mixture will exhibit nonhazardous or less hazardous characteristics. The processes have, therefore, been in use for some time so that process reliability for some applications is fairly well demonstrated. Solidification/ stabilization techniques can be grouped according to the nature of the fixation agent used in each process. The following fixation techniques can be applied for in-place lagoon closure:

(a) Cement/based.
(b) Lime-based.
(c) Thermoplastic.
(d) Organic polymer.

Applicability/uncertainties -- Some fixation processes have been found to be applicable to the treatment and disposal of various hazardous wastes, as well as radioactive materials. Use of these techniques to treat nonradioactive waste, however, can be restricted due to economic considerations. Also, not all fixation processes are suitable for treating complex, nonhomogeneous wastes. Chemical compatibility between the waste and the fixation agent can be problematic. Therefore, consideration of waste constituents must be taken prior to selecting a fixation process.

Some wastes contain impurities that can impede the setting and curing process of solidification. The resultant product can then be unstable or friable. For example, organics at concentrations of greater than 10 percent can interfere with solidification. Other impurities, including salts of zinc, copper, lead, manganese, and tin; sodium salts of arsenate, borate, phosphate, iodate, and sulfide; and sulfate salts, act as setting retarders

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that may significantly reduce the strength of the solidified product. Very fine particulate matter, such as fine silts and silty clays, can also weaken a waste cement product, as these materials may coat the larger solids in the waste, and weaken the bond between the large waste particles and the cement.

Performance verification -- Following a compatibility assessment, which initially determines the effectiveness of a particular fixation process for a specific closure application, quality control during construction represents an important performance verification step. Some of the construction variables that need to be addressed are the following:

(a) Sludge characteristics such as moisture content and viscosity (grab samples).
(b) Composition of fixing agents such as free lime content (grab samples).
(c) Sludge mixing or blending to achieve homogeneity.
(d) Mixing and blending of fixation agents.
(e) Mixture ratio of sludge to fixation additives (predetermined during bench scale or pilot tests).
(f) Mixture characteristics of temperature and moisture content.

After it is placed in its final disposal location, the fixed waste product should be disturbed as little as possible in order to preserve its physical integrity and not disrupt the curing process. Therefore, any destructive-type test methods are discouraged for long-term performance verification. Alternatively, nondestructive or remote methods are recommended. Suggested test methods include the following:

(a) Visual inspection.
(b) Groundwater monitoring.
(c) Leach testing.
(d) Physical property testing of grab samples collected during processing, such as unconfined compressive strength test to determine long-term bearing capacities.

Economic considerations -- In general, solidification/stabilization processes represent a relatively high cost remedial action alternative. Proportions and quantities of required fixation additives vary tremendously with the specific waste stream application, and the cost effectiveness of this technology can be determined only after bench-scale tests are completed. Typical unit costs for solidification/stabilization additives range

trom approximately $3.00 per 100 pounds of raw waste to be processed through cement-based and pozzolanic techniques to approximately $19 to $28 per 100 pounds tor thermoplastic and organic polymer techniques.

2.3.6.2 Chemical, biological, and physical treatment.

Description -- This final category of technologies is presented as a potential in-place closure strategy, since many of the waste streams encountered at military installations will require some form of treatment prior to containment or closure of the lagoon area. Other current research and development contractors to USATHAMA are assessing chemical, biological, and physical treatment tecnniques. Some of the treatment processes being investigated are as follows:

(a) Sulfur-based reduction (chemical).
(b) Sodium borohydride reduction (chemical).
(c) Base-initiated decomposition (chemical).
(d) Reduction cleavage (chemical).
(e) Chemically-initiated free radical treatment (chemical).
(f) Physically-induced free radical decomposition, including gamma irradiation, electron beam processing, and UV pnotolysis (physical).
(g) Thermal treatment through wet air oxidation or incineration (physical).
(h) Biodegradation (biological).

Applicability/uncertainties -- Most of the chemical, physical, and biological tecnnologies are in the developmental stage, where research and development and pilot studies are being conducted to assess their potential application to the treatment of explosives-contaminated lagoon areas. Only wet air oxidation, incineration, and biodegradation techniques are at a high state of technology development and are potentially available for full-scale application. The applicability and performance of all chemical, physical, and biological technologies to treat actual waste materials in lagoons remains questionable. The reaction kinetics of the various processes have not been quantified, and the reaction by-products for treatment of explosives are not fully understood.

In short, while treatment techniques appear promising for application at explosive waste lagoons, no technology has a successful past history of application, and most remain in the research and development stage.

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Performance verification. Since the treatment technologies
are in the developmental stage, no performance testing approach-
es have been assessed.

Economic considerations -- The cost of full-scale implemen-
tation of treatment techniques may limit their potential appli-
cation, since all require additional bench- and pilot-scale
testing, and commercial full-scale equipment is not available.

2.4 Evaluation of potential alternatives. The seven general
categories of closure technologies addressed in Sections 3
through 8 of this report are evaluated in this section with re-
spect to applicability for in-situ lagoon closure. Technologies
are rated, relative to one another, in the following three dis-
tinct categories:

(a) Applicability to specific site environmental condi-
      tions.
(b) Waste compatibility.
(c) Implementation factors that impact closure.

2.4.1 Applicability to specific environmental conditions.
Table 1 is a decision guide matrix that presents an assessment
of the applicability of closure technologies to specific site
environmental conditions. Technologies are rated as having high
applicability, moderate applicability, or low applicability to
specific site environments. In cases where a technology is not
influenced by environmental conditions, a not sensitive rating
is assigned to indicate that the technology is not sensitive to
or not influenced by the environmental condition of concern.

2.4.1.1 Site environmental conditions. Closure site envi-
ronmental parameters are defined in Volume 1 of this report, and
are summarized in the subsections that follow:

Precipitation -- Average annual precipitation is a major
factor in the rate at which contaminants can infiltrate the
soil. At sites with unlined lagoons, the amount of net infiltra-
tion as estimated by annual precipitation is the driving force
for the vertical migration of contaminants.

High annual precipitation is defined as 41 to 60 inches per
year, moderate as 21 to 40 inches per year, and low as 0 to 20
inches per year.

Subsurface permeability -- Permeability governs the rate at
which water moves through the subsurface soil/bedrock profile.

TABLE 1.   RATING OF THE APPLICABILITY OF CLOSURE TECHNOLOGIES TO SPECIFIC SITE ENVIRONMENTAL CONDITIONS

Site environmental conditions	Soil cap systems	Nonsoil caps	Nonsoil liners	Surface-water diversion	Groundwater diversion	Groundwater flow manipulation	Processing/ treatment
Precipitation (annual)							
High (41-60 inches/yr)	◐	●	I	●	I	I	I
Moderate (21-40 inches/yr)	●	●	I	●	I	I	I
Low (0-20 inches/yr)	●	○	I	◐	I	I	I
Subsurface permeability							
High permeability	I	I	●	I	○	◐	I
Moderate permeability	I	I	◐	I	◐	◐	I
Slow permeability	I	I	○	I	◐	○	I
Groundwater table (depth from surface)							
Shallow (0-15 feet)	I	I	●	I	●	●	I
Moderate (15-100 feet)	I	I	◐	I	◐	◐	I
Deep (>100 feet)	I	I	○	I	○	○	I
Flooding potential							
High	○	○	○	○	I	I	I
Moderate	○	○	○	◐	I	I	I
Low	I	I	I	●	I	I	I
Geological subsurface stability							
High	●	●	●	●	●	●	I
Moderate	◐	◐	◐	◐	◐	◐	I
Low	○	○	○	○	○	○	I

Key:

● High applicability
◐ Moderate applicability
○ Not applicable to low applicability
I Insensitive -- technology not influenced by given site conditions

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Types of subsurface conditions are categorized as highly permeable, moderately permeable, and slowly permeable. This is a summary category combining information on the soils, bedrock, and unconsolidated sediments directly beneath each site. Permeability is discussed in terms of hydraulic conductivity in the paragraphs that follow.

High permeability ($100-10^5$ gal/day/sq ft) -- Any highly permeable subsurface (alluvium, glacial outwash, gravel, or sandy formations), geological conditions of fractured bedrock, or shallow limestone bedrock, which results in a Karst topography or sinkholes, solution channels, springs, and caverns are conducive to subsurface migration of contaminants and pose a potential high risk to in-situ closure of lagoons.

Moderate permeability (1-99 gal/day/sq ft) -- Moderate permeability subsurfaces are common in regions with compound soil layers. Compound soil layers provide an environment where a thin, relatively impermeable formation is located above a permeable formation (e.g., cemented hardpan over sandy alluvium, or a layer of glacial till over outwash). The impermeable layer restricts vertical water movement so that water flows horizontally along the top of the dense layer. Breaks in the impermeable layer result in channels from the surface to permeable formations below. Moderately permeable soils may include silty sands and silt.

Low permeability (<1 gal/day/sq ft) -- Slowly permeable soils (glacial till, colluvium, lacustrine sediments, or other silty and clayey formations) and/or tight bedrock (unfractured shale) retard vertical migration of water and contaminants and may serve as possible natural liners to restrict seepage from lagoons closed in place.

Groundwater table -- The depth to groundwater beneath a waste disposal lagoon is of major importance to an in-situ closure program. Shallow water tables can act as contaminant migration pathways and, once contaminated, extensive and long-term groundwater cleanup problems may result. In some instances, a shallow water table may intersect the bottom of a lagoon thereby leaching contaminants out of the waste. A shallow water table also implies a limited potential for contaminant attenuation in the unsaturated zone soils underlying a lagoon, and, therefore, a higher potential exists for contamination of the shallow water table.

Depth to groundwater is also a major factor considered by many state agencies in defining closure requirements and options. Groundwater table depths are defined as follows:

(a) Shallow -- 0 to 15 feet from ground surface.
(b) Moderate -- 15 to 100 feet from ground surface.
(c) Deep -- greater than 100 feet from ground surface.

Flooding potential -- Flooding potential is a measure of the potential severity and frequency of flooding. Flooding potential is categorized as follows:

(a) High -- regular flooding occurs.
(b) Moderate -- occasional flooding.
(c) Low -- no flooding; outside 100-year flood plain.

Flooding is a major concern for in-situ closure of waste lagoons. A flood could destroy the cover and wash out the lagoon contents to streams and rivers. An in-situ closure design must address the issue of potential flooding. Some Federal and state hazardous waste regulatory requirements place restrictions on facilities located within a flood plain.

Geological subsurface stability -- Geological subsurface stability is an important parameter that affects closure technology selection. Shallow carbonate bedrock (limestone or dolomite), for example, is often karstic, i.e., the rock has been eroded and dissolved in local areas, and sinkholes and solution channels have formed. In such environments, the ground surface is unstable and final in-situ closure of lagoons may not be a feasible alternative. Other geological features that may determine final closure alternatives are seismic risk zones and major fault zones. Subsurface stability is categorized as follows:

(a) High -- high stability subsurface, e.g., metamorphic and igneous rock, shale; no seismic risk.
(b) Moderate -- moderate stability subsurface, e.g., carbonate bedrock, sandstone.
(c) Low -- low stability subsurface, -- e.g., karstic formations, major fault zones.

2.4.1.2 Environmental applicability rating. The technology assessment for site applicability is presented in Table 1. The assigned ratings are best explained by referring to Sections 3 through 8 of this report where site environmental considerations are discussed in detail for each closure technology.

2.4.2 Waste compatibility with closure technologies. In Table 2 closure technologies are rated for compatibility with lagoon wastes. Waste parameters of primary concern include several chemical and physical waste characteristics.

Chemical waste constituents that are included in the rating system are explosives, organic solvents, and heavy metals. The closure technologies are rated for compatibility with wastes with high concentrations of these constituents.

The primary physical parameters that may affect the selection of closure technologies are the moisture content of the waste and the waste-bearing capacity.

For this evaluation, moisture content is defined as follows:

(a) High moisture content -- greater than 60 percent liquid by weight.
(b) Moderate moisture content -- 40-60 percent liquid by weight.
(c) Low moisture content -- less than 40 percent liquid by weight.

Bearing capacity is categorized as high, moderate, or low, in terms of California Bearing Ratio (CBR) where:

(a) High   = >3 CBR
(b) Moderate = 1-3 CBR
(c) Low   = <1 CBR

2.4.2.1 Waste compatibility assessment rating. In this assessment, each technology is rated as highly compatible, moderately compatible, incompatible to poorly compatible, or insensitive to waste characteristics. The ratings are presented in Table 2. A thorough discussion of waste compatibility with closure technologies can be found in the body of the report where individual technologies are covered in depth.

2.4.3 Implementation factors that impact closure plans. In Table 3 closure technologies are assessed relative to implementation factors that can impact closure plans. The implementation factors considered include the following:

(a) State regulatory requirements.
(b) Regulatory acceptability.
(c) Long-term integrity.
(d) Public acceptability.

TABLE 2. LAGOON WASTE COMPATIBILITIES WITH CLOSURE TECHNOLOGIES

Waste characteristics	Soil cap systems	Nonsoil caps	Nonsoil liners	Surface-water diversion	Groundwater diversion	Groundwater flow manipulation	Chemical treatment	Physical treatment	Biological treatment	Stabilization
Chemical constituents										
Explosives	●	●	●	I	●	I	◐	◐	◐	●
Organic solvents	◐	◐	O	I	◐	I	●	●	●	◐
Heavy metals	●	●	●	I	●	I	●	◐	O	●
Physical characteristics										
Moisture content										
High moisture content (>60 percent by weight)	O	O	◐	I	I	I	●	●	●	◐
Moderate moisture content (40 to 60 percent)	◐	◐	●	I	I	I	◐	◐	●	◐
Low moisture content (<40 percent)	●	●	●	I	I	I	◐	◐	◐	◐
Bearing capacity										
High	●	●	●	I	I	I	I	I	I	I
Moderate	◐	◐	●	I	I	I	I	I	I	I
Low	O	O	◐	I	I	I	I	I	I	I

Key:

● High compatibility.
◐ Moderate compatibility.
O Incompatible to low compatibility.
I Insensitive -- technology not affected by waste characteristic.

TABLE 3. RATING OF IMPLEMENTATION FACTORS THAT IMPACT CLOSURE PLANS

Implementation factors	Technologies							
	Soil cap systems	Nonsoil caps	Nonsoil liners	Surface-water diversion	Groundwater diversion	Groundwater flow manipulation	Treatment	Stabilization
State regulatory requirements	◐	◐	◐	◐	○	○	●	●
Regulatory acceptibility	◐	◐	◐	◐	◐	○	●	●
Long-term integrity/reliability	◐	○	○	●	◐	○	●	◐
Public acceptability	◐	◐	◐	◐	◐	◐	●	●
Long-term operating/maintenance requirements	◐	◐	○	◐	●	○	●	◐
Future land use options	○	○	○	◐	●	●	●	○
Safety	◐	◐	◐	◐	◐	◐	○	○
Historical applications	●	○	◐	●	◐	◐	○	◐

Key:

Impact on closure technologies

- ● Favorable
- ◐ Neutral
- ○ Less favorable

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(e)   Long-term operating and maintenance requirements.
(f)   Future land use options.
(g)   Safety.
(h)   Historical application.

The potential impact on closure technologies is rated as favorable, neutral, or less favorable.

2.5   Development of trial in-place closure scenarios.

2.5.1   General. This subsection will point out the application of the decision-making flow diagrams and the evaluation tables to the assessment of potential in-place closure strategies. Three trial scenarios are developed based on assumed waste characteristics and site conditions that have been found to occur in many of the Army installations described in Volume I of this Task Order. The scenarios are representative of conditions that exist, but they do not attempt to encompass the full range of potential waste and environmental conditions that may be found at all of the Army installations. The three trial scenarios for remedial action discussed herein include the following:

(a)   Explosive wastes disposed of in unlined areas exhibiting poor bedrock and groundwater conditions: in-place closure is not an option for remedial action.
(b)   Explosive wastes disposed of in unlined sandy soil areas in a dry desert-like climate: in-place closure restricted to infiltration control measures.
(c)   Nonexplosive inorganic and organic wastes disposed of in unlined lagoons underlain by permeable soils and an extensive confining bedrock layer: in-place closure incorporates complete site isolation techniques.

For each of the remedial-action scenarios, the basic waste characteristics and key site conditions are presented, and the evaluation highlights are discussed. To perform the evaluation, the appropriate decision-variable steps are traced through each of the matrix flow diagrams (Figures 3 through 8), just as the installation commander would do for a specific Army installation. Each of the matrix flow diagrams is highlighted, indicating the path of the evaluation (indicated by darkened outlines) for the trial scenarios. The matrices are designed to lead to one of two conclusions:

(a)   The waste characteristics and site conditions are not compatible for any remedial action, so in-place closure may not be an option.

(b)   Specific remedial actions can be applied successfully
      to mitigate the environmental concerns during in-
      place closure.

In the situations where the second conclusion is reached,
the installation commander is directed to address specific
evaluation considerations described within the evaluation tables
(Tables 1 through 3). The highlights of this evaluation are in-
cluded for each trial scenario as well. The final result of each
scenario's trial evaluation is a recommendation for an appropri-
ate strategy for in-place closure.

2.5.2   Scenario 1 -- In-place closure is not an option for
remedial action at explosive waste disposal areas. The specific
waste characteristics and site conditions of concern for this
scenario are presented as follows:

(a)   **Waste Characteristics.**

      - Explosive wastes and sediments have been disposed of
        in unlined lagoon areas or natural drainage
        ditches.
      - Regulatory requirements prohibit closure of these
        areas until the wastes are made nonreactive.
      - Wastes and sediments can be treated to desensitize
        reactivity.
      - Wastes cannot be treated to render them nonhazardous
        and nonleachable.
      - Wastes exhibit high moisture content.

(b)   **Site conditions.**

      - Disposal areas are located outside the flood plain.
      - Site soils are silty sands exhibiting moderate per-
        meability rates.
      - Area climate has moderate annual precipitation, cre-
        ating moderate net infiltration through the site.
      - There are shallow depths to the groundwater table.
      - Groundwater represents a usable aquifer.
      - Site is underlain by limestone bedrock, which is
        prone to development of extensive sinkholes and
        solution channels.
      - No acceptable alternate locations are available on-
        site to replace wastes.

These waste characteristics and site conditions are representative of many Army installation locations where major concerns exist for direct contamination of groundwater by explosive contaminants and where sinkhole development is prevalent. The evaluation process for this scenario is traced in Figure 9 and the evaluation highlights are described in subsection 2.5.2.1. A summary sketch of the conclusions of this evaluation is presented in Figure 10.

2.5.2.1 Evaluation highlights. The evaluation process applicable to this scenario is as follows:

(a)   The decision matrices lead to the conclusion that in-place lagoon closure is not an appropriate remedial action strategy.

(b)   Although the explosive wastes and sediments can be desensitized or treated to eliminate reactivity concerns, they remain hazardous and leachable.

(c)   Seasonal flooding and potential runoff conditions create concerns over contaminant migration into runoff or surface-water supplies.

(d)   Remedial actions can be incorporated to minimize concerns over flooding and surface runoff contact with the contaminated areas.

(e)   The silty soils and moderate rainfall present a moderate net infiltration rate through the contaminated area.

(f)   The infiltration generates contaminated leachate, which migrates through the shallow depths of subsurface soils to groundwater.

(g)   Remedial actions can be incorporated to reduce contaminated infiltration. If leachate generation was the only concern, in-place closure could be implemented successfully.

(h)   The limestone bedrock topography is shallow and highly porous, and the creation of sinkholes and solution channels is prevalent.

(i)   There exists a high potential for contaminant migration into the groundwater through bedrock solution channels.

(j)   The shallow depth to groundwater and the seasonal fluctuation of water table elevations (bringing groundwater in contact with the wastes) create concern over direct contaminant migration into groundwater.

Waste and lagoon area characterization.
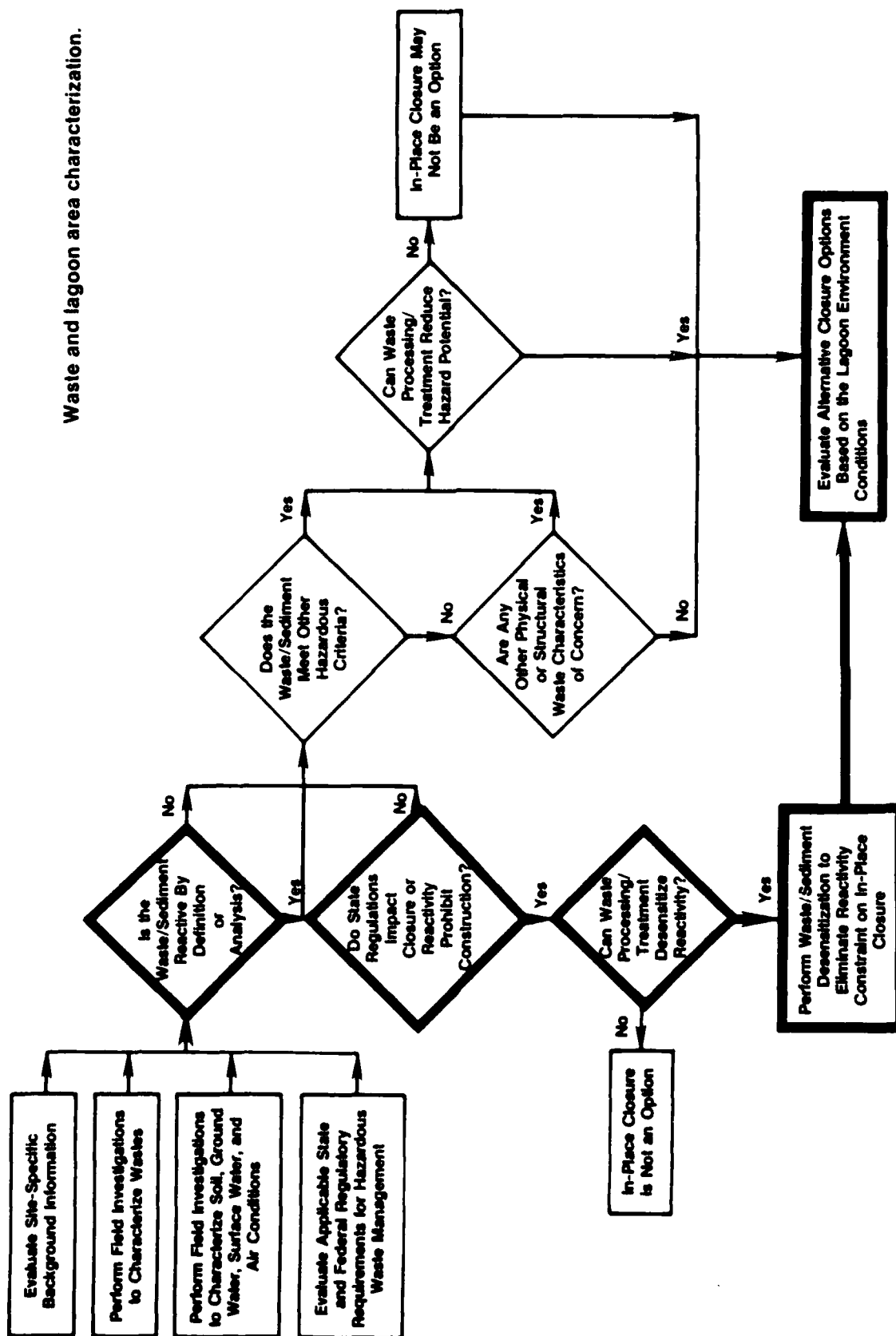
Figure 9. Evaluation decision process for scenario 1.
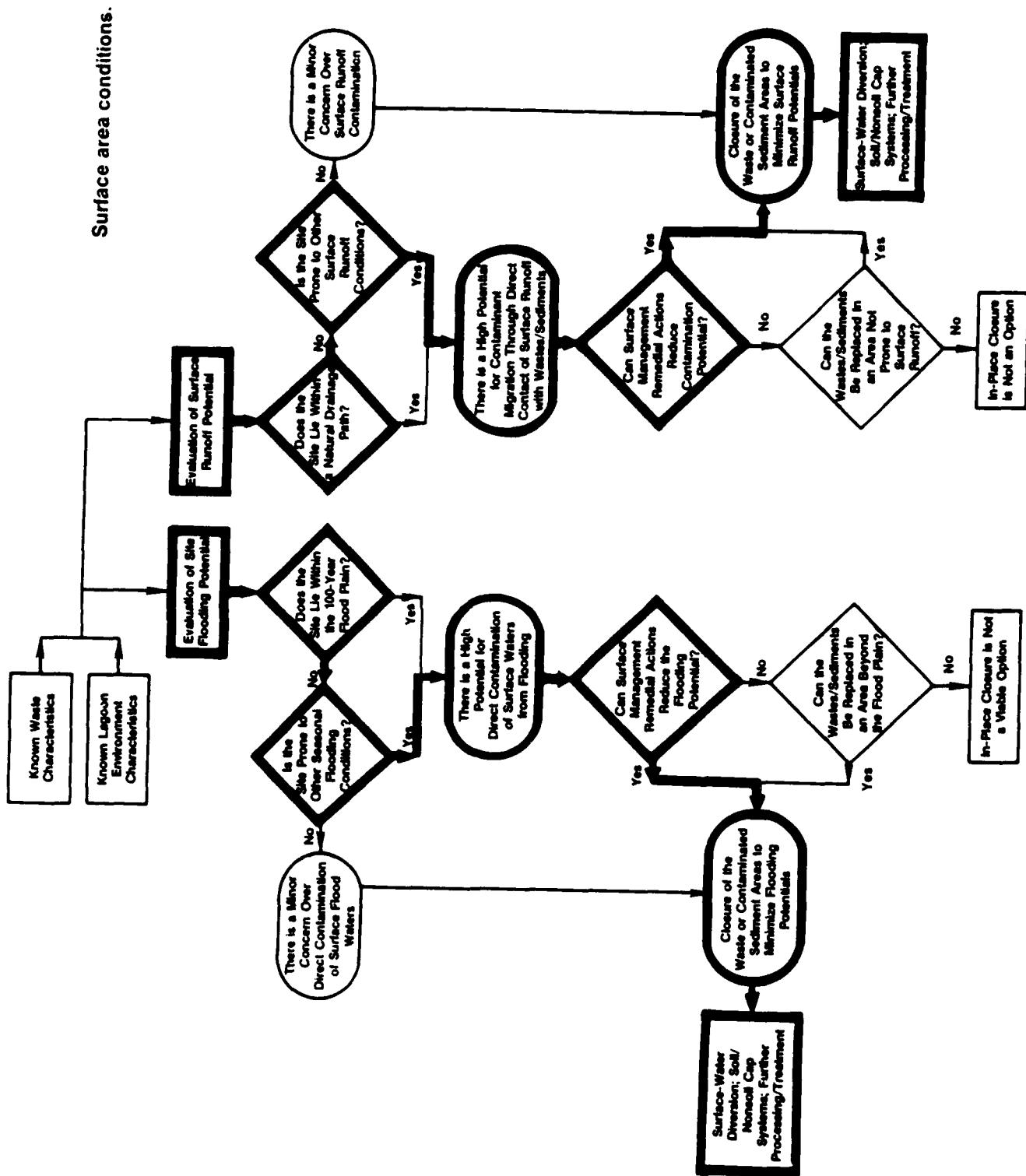
56

Surface area conditions.

Figure 9. (Continued)

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Figure 9. (Continued)

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Figure 9. (Continued)

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Figure 9. (Continued)

Hydrogeological conditions.

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Groundwater conditions.
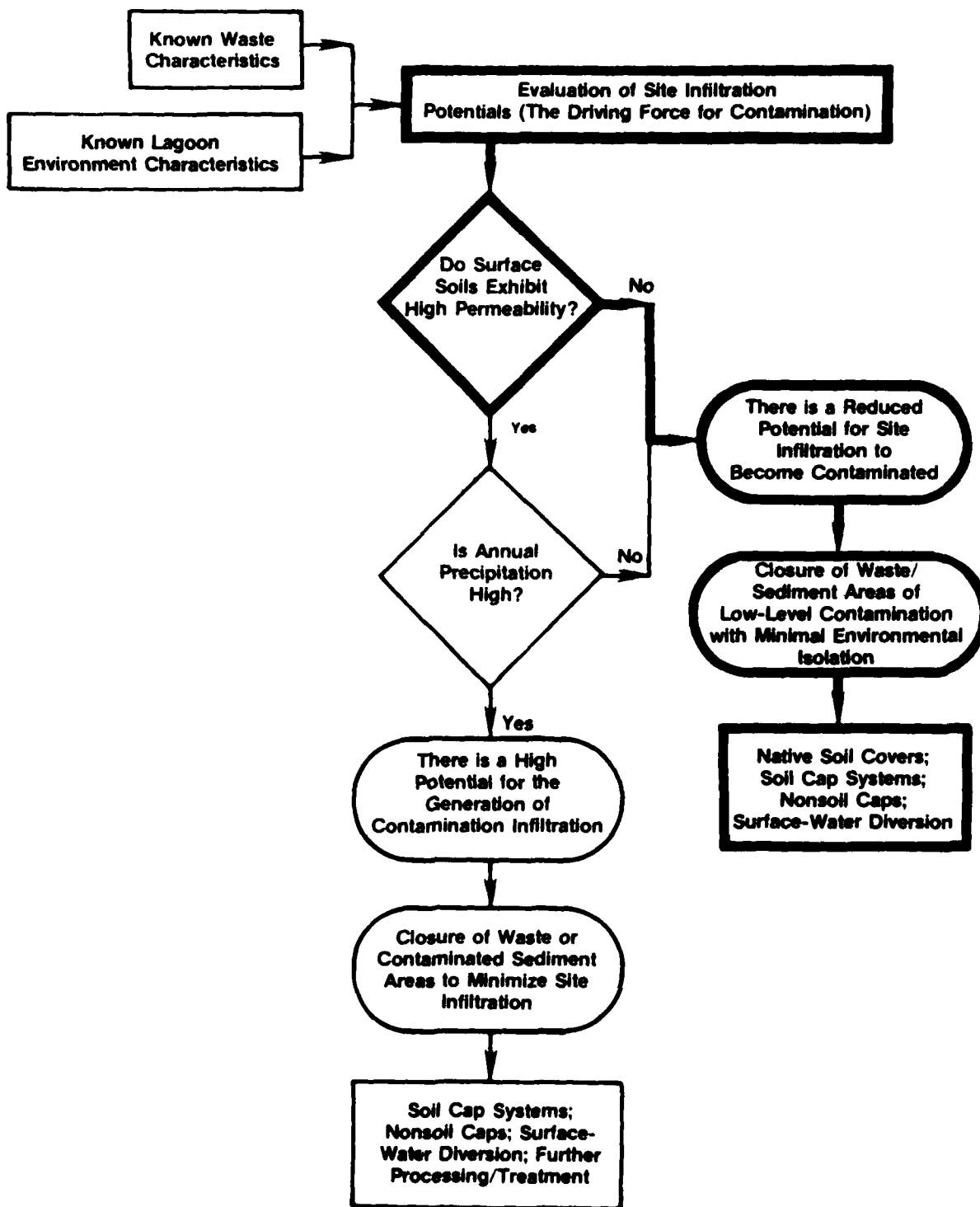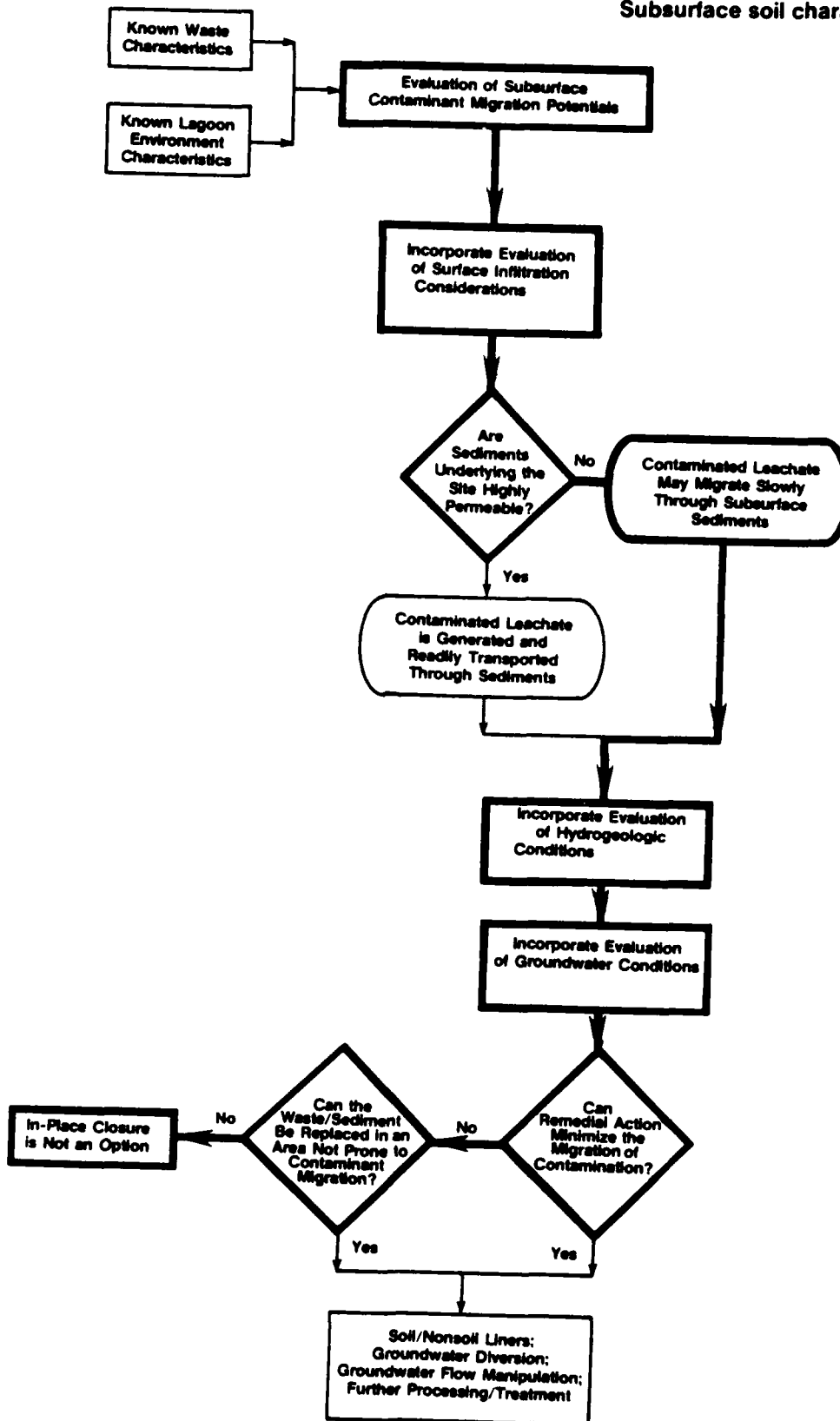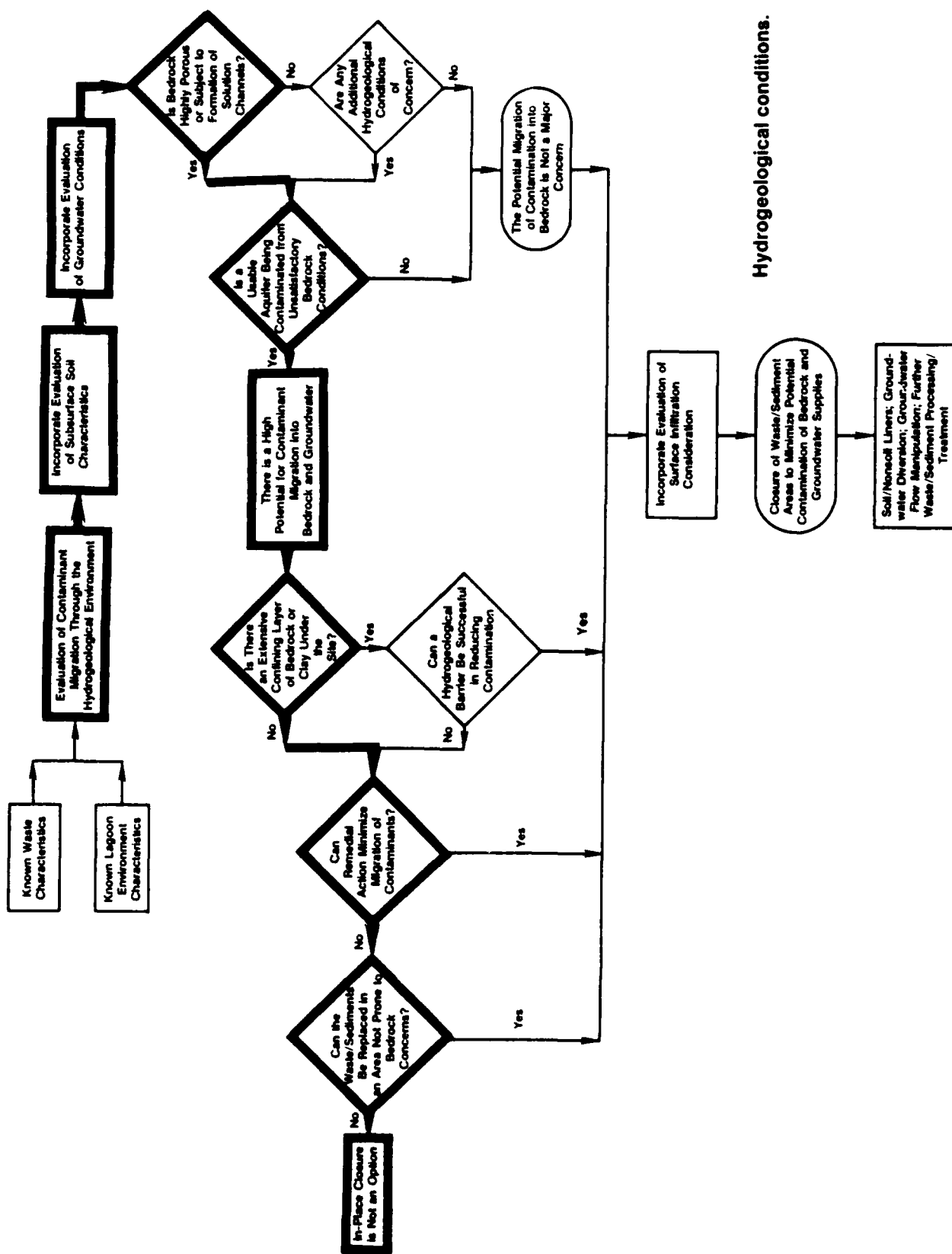
Figure 9. (Continued)
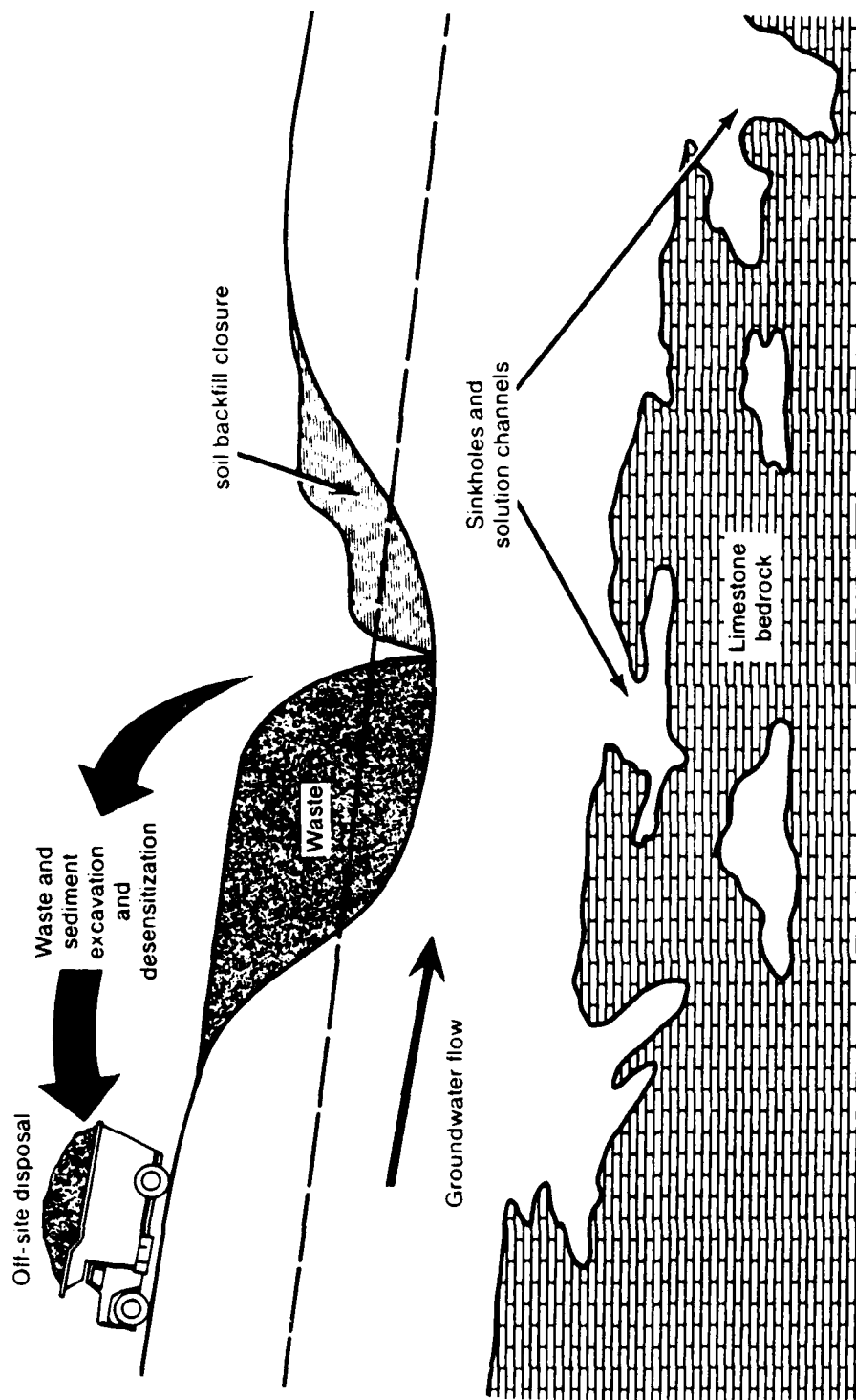
Figure 10. Off site disposal of explosive wastes and sediments.

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(k) These contamination concerns are constraints to in-place closure, unless the wastes and contaminated sediments can be removed and replaced in less sensitive areas.

(l) Since the wastes cannot be removed and replaced, the sources of groundwater contamination cannot be mitigated, and in-place closure is not an appropriate remedial action.

(m) The contaminated wastes and sediments should be excavated for destruction or offsite disposal.

2.5.3 Scenario 2 -- In-place closure restricted to infiltration control measures at explosive waste disposal areas. The specific waste characteristics and site conditions that are representative of this scenario are presented as follows:

(a) Waste characteristics.

- Explosive wastes and sediments disposed of in unlined lagoon areas or natural drainage ditches.
- Regulatory requirements prohibit closure of these disposal areas until the wastes are rendered non-reactive.
- Wastes and sediments can be treated to desensitize reactivity.
- Wastes can be treated to reduce their leaching potential.
- Wastes and sediments exhibit a low moisture content.

(b) Site conditions.

- Disposal areas located outside the flood plain.
- Seasonal flash floods can occur, but, on the average, low annual precipitation exists.
- Climate is dry and desert-like with overall net evaporation (extremely low infiltration).
- Deep layers of unconsolidated sandy sediments underlying the site.
- Deep depths to groundwater table.

These waste characteristics and site conditions are representative of Army installations that are located in arid desert-like environments. In many of these installations, annual rainfall is extremely low, but high intensity and short duration storms create flash flooding conditions. The sites are typically underlain by sandy soils that extend deep below the disposal areas, and shallow groundwater depths are not of concern. The evaluation process for this scenario is traced through the decision matrices of Figure 11, and the evaluation highlights are described in subsection 2.5.3.1. A summary sketch depicting the conclusions of this evaluation is presented in Figure 12.

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Waste and lagoon area characterization.

Figure 11. Evaluation decision process for scenario 2.

64

Surface area conditions.

```
Known Waste Characteristics
Known Lagoon Environment Characteristics

Evaluation of Site Flooding Potential
Evaluation of Surface Runoff Potential

Does the Site Lie Within the 100-Year Flood Plain?  — Yes →
Is the Site Prone to Other Seasonal Flooding Conditions?  — Yes →
  No →
There is a Minor Concern Over Direct Contamination of Surface Flood Waters

There is a High Potential for Direct Contamination of Surface Waters from Flooding

Can Surface Management Remedial Actions Reduce the Flooding Potential?
  Yes →
  No →
Can the Wastes/Sediments Be Replaced in an Area Beyond the Flood Plain?  — Yes →

Closure of the Waste or Contaminated Sediment Areas to Minimize Flooding Potentials

Surface-Water Diversion; Soil/Nonsoil Cap Systems; Further Processing/Treatment

Does the Site Lie Within a Natural Drainage Path?  — Yes →
Is the Site Prone to Other Surface Runoff Conditions?  — Yes →
  No →
There is a Minor Concern Over Surface Runoff Contamination

There is a High Potential for Contaminant Migration Through Direct Contact of Surface Runoff with Wastes/Sediments

Can Surface Management Remedial Actions Reduce Contamination Potential?
  Yes →
  No →
Can the Wastes/Sediments Be Replaced in an Area Not Prone to Surface Runoff?  — Yes →

Closure of the Waste or Contaminated Sediment Areas to Minimize Surface Runoff Potentials

Surface-Water Diversion; Soil/Nonsoil Cap Systems; Further Processing/Treatment
```

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```
┌─────────────────┐
│  Known Waste    │───┐
│ Characteristics │   │      ┌──────────────────────────────────────┐
└─────────────────┘   │      │      Evaluation of Site Infiltration  │
                      ├─────▶│ Potentials (The Driving Force for     │
┌─────────────────┐   │      │           Contamination)              │
│  Known Lagoon   │   │      └──────────────────────────────────────┘
│ Environment     │───┘                         │
│ Characteristics │                             ▼
└─────────────────┘
```

Do Surface Soils Exhibit High Permeability? — No →

Yes ↓

There is a Reduced Potential for Site Infiltration to Become Contaminated

Is Annual Precipitation High? — No →

Yes ↓

There is a High Potential for the Generation of Contamination Infiltration

Closure of Waste/ Sediment Areas of Low-Level Contamination with Minimal Environmental Isolation

Closure of Waste or Contaminated Sediment Areas to Minimize Site Infiltration

Native Soil Covers; Soil Cap Systems; Nonsoil Caps; Surface-Water Diversion

Soil Cap Systems; Nonsoil Caps; Surface-Water Diversion; Further Processing/Treatment

Figure 11.   (Continued)

Figure 11. (Continued)

Figure 11. (Continued)

Hydrogeological conditions.

68

Groundwater conditions.

Figure 11. (Continued)

Figure 12. Application of infiltration control measures at an explosive waste lagoon area.

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2.5.3.1 Evaluation highlights. The evaluation process applicable to this scenario is as follows:

(a) The decision matrices point to successful application of various appropriate remedial-action approaches.

(b) The wastes and contaminated sediments can be successfully rendered nonreactive and nonleachable.

(c) The dry climate creates only a minor concern about net infiltration of contaminants.

(d) Although the waste disposal areas are not located within a flood plain, there is a high potential for surface runoff and flash flood contamination.

(e) Remedial actions can be incorporated to control the flooding and surface runoff concerns minimizing potential surface contamination potentials.

(f) The site's deep layers of sandy soils are highly permeable, but only minimal quantities of infiltration are generated (except during seasonal occurrence of high intensity rainfalls).

(g) Remedial actions can be successfully incorporated to minimize contaminated infiltration.

(h) With the deep depths to groundwater and small quantities of contaminated leachate that can be generated, groundwater contamination will probably not be a significant concern.

(i) The wastes and sediments can be left in-place and an in-place closure strategy can be incorporated to minimize surface-water and infiltration concerns.

(j) The technology evaluation tables should be used to limit the shopping list of potential remedial actions recommended within the decision matrices (the matrices pointed to use of surface-water diversion, soil cap systems, nonsoil cap systems, further processing/treatment of the wastes and sediments, soil and nonsoil liners, groundwater diversion, and groundwater flow manipulation).

(k) From the evaluation tables, the following technologies have little or no application to this scenario:

- Complex cap systems (both soil and nonsoil cap systems), since precipitation is so low.
- Liner systems, since net infiltration is very low.
- Groundwater diversion and flow manipulation, since depth to groundwater is deep.

(1)   Recommended remedial actions for this scenario include
       the following:

       - Perform waste and sediment desensitization and fur-
         ther processing that can solidify or stabilize the
         waste material.
       - Placement of a native soil cap or single clay layer
         that is graded and revegetated to direct runoff
         away from the waste area.
       - Incorporate surface-water diversion techniques as
         part of the site grading activities to carry run-
         off away from the site.

2.5.4   Scenario 3 -- In-place closure through incorporation
of site isolation techniques at an unlined nonexplosive waste
lagoon area. The specific waste characteristics and site condi-
tions of concern for this scenario are presented as follows:

(a)   Waste characteristics.

       - Nonexplosive wastes and sediments disposed of in un-
         lined waste lagoon areas.
       - No reactive wastes are included; the wastes are a
         combination of inorganic waste sludges, predomi-
         nantly electroplating wastes, but some organic
         wastes can be present.
       - Sludges can be stabilized or solidified to reduce the
         leaching of heavy metals.
       - Wastes and sediments exhibit moderate moisture con-
         tent.

(b)   Site conditions.

       - Disposal areas are located outside the flood plain.
       - Disposal areas are not prone to significant surface
         runoff conditions.
       - High annual precipitation.
       - Site soils exhibit relatively high permeabilities,
         and high net infiltration results.
       - Groundwater flows within the unconsolidated sedi-
         ments, and shallow depths to groundwater exist.
       - A relatively deep contining bedrock layer extends
         beneath the site.

These waste characteristics and site conditions are indicative of Army installations with complex waste disposal and site hydrogeologic conditions. Heavy metal sludges have been deposited above relatively permeable soils, and the climatic conditions promote infiltration. The evaluation process for this scenario is traced in Figure 13, and the evaluation highlights are described in subsection 2.5.4.1. A summary sketch of the conclusions of this remedial action evaluation is presented in Figure 14.

2.5.4.1 Evaluation highlights.

(a) The decision matrices point to successful application of various potential remedial action approaches.
(b) Inorganic wastes can be stabilized/solidified to reduce potential leaching, but the contained organic wastes may not be bound up completely.
(c) With the presence of highly permeable surface and subsurface soils and with high precipitation rates, high infiltration potentials are created.
(d) Although flooding is not a concern, surface runoff can occur, and contaminated infiltration and leachate generation are major concerns.
(e) Remedial actions can be incorporated to minimize surface runoff contamination and subsurface contaminant migration.
(f) There exists a significant potential for groundwater contamination through gradual migration of organic and inorganic constituents through the sandy soil.
(g) Since the groundwater does not come in contact with the base of the disposal areas, remedial actions can be implemented to successfully reduce groundwater contamination.
(h) The decision matrices conclude with various remedial-action recommendations, including surface-water diversion, soil and nonsoil cap systems, further treatment of the wastes, soil and nonsoil liners, ground-water diversion, and flow manipulation.
(i) With the site-specific conditions outlined for this scenario, the list of potential remedial actions cannot be reduced further. The following conditions could influence the recommendation of a specific remedial-action strategy:

- Surface-water diversion and site grading are necessary components of an in-place closure approach for this scenario.

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Waste and lagoon area characterization.

Figure 13. Evaluation decision process for scenario 3.
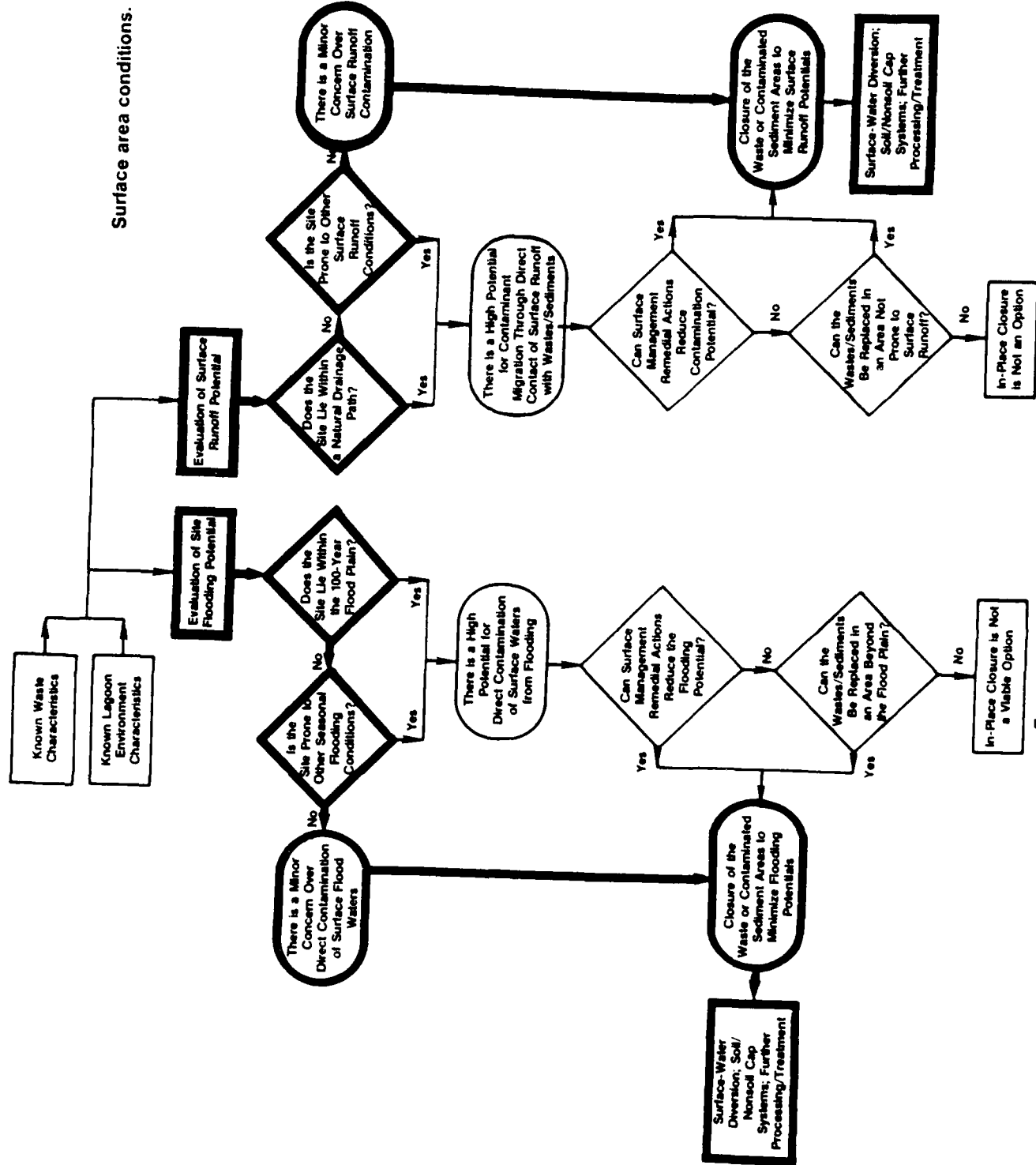
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Surface area conditions.

Figure 13. (Continued)

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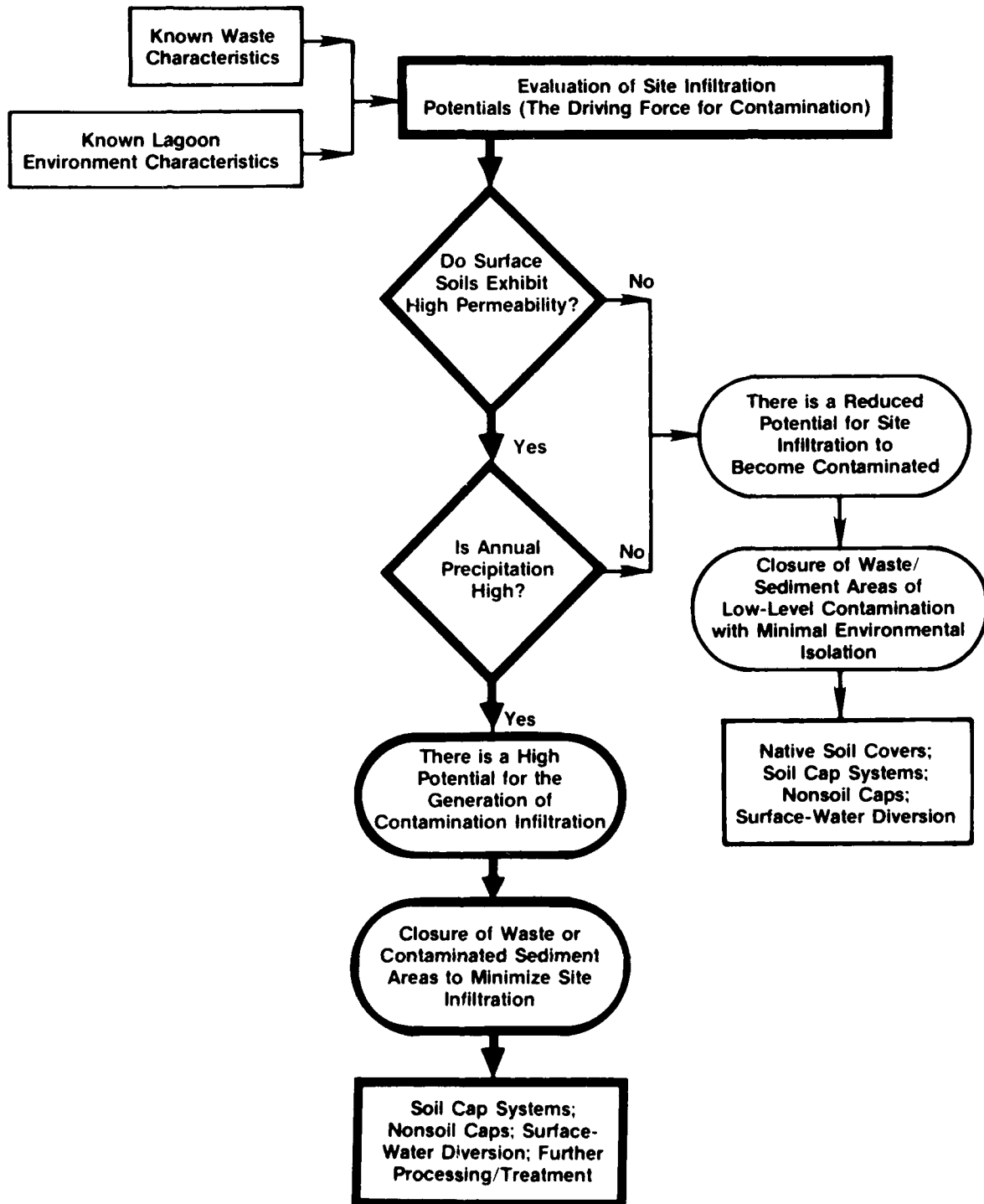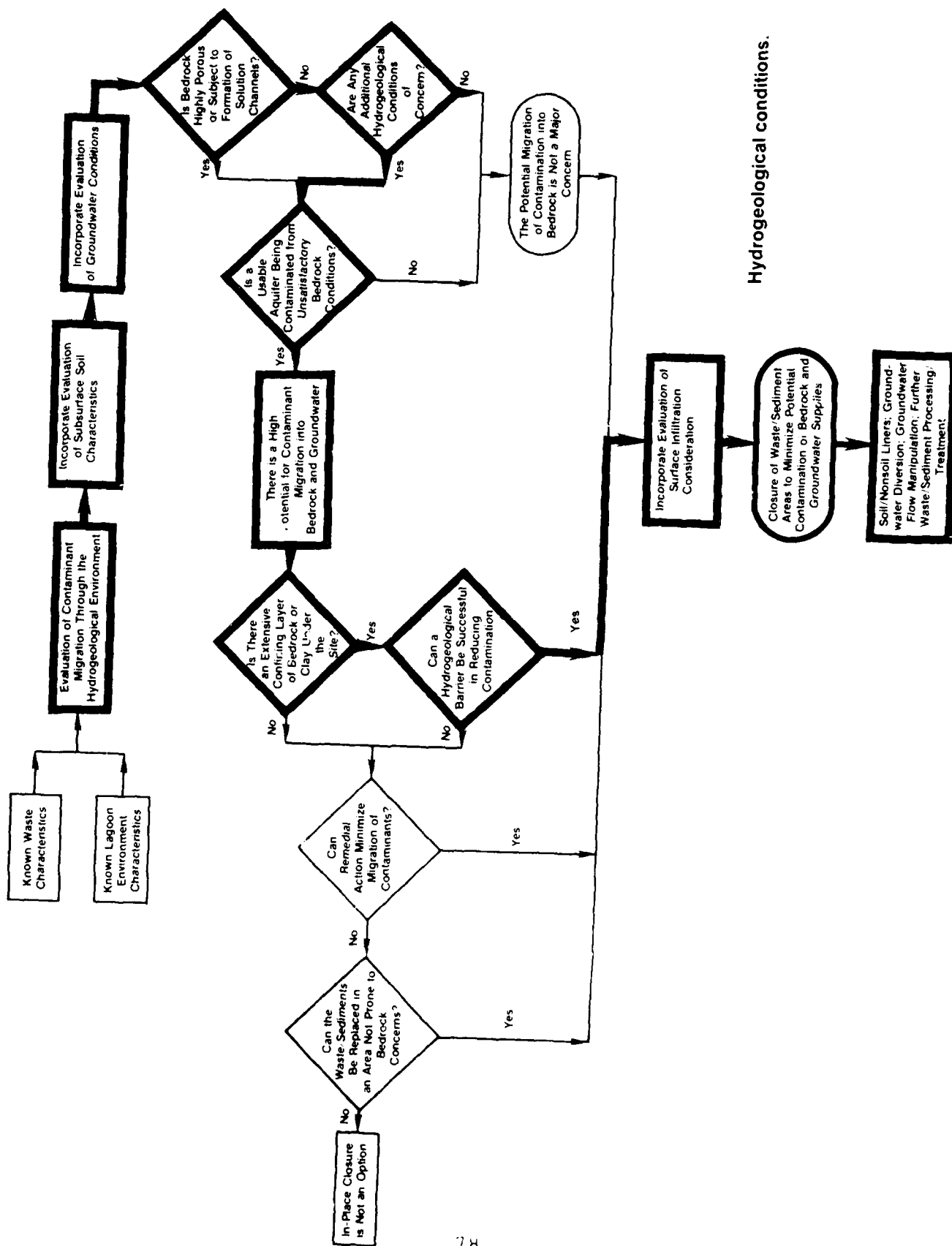
Figure 13. (Continued)

Figure 13. (Continued)

Hydrogeological conditions.

MICROCOPY RESOLUTION TEST CHART
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Groundwater conditions.

Figure 13. (Continued)

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Figure 14. Application of complete site isolation measures for a nonexplosive waste disposal area.

- The use of a complex soil cap system or nonsoil cap system is necessary to reduce site infiltration and help isolate the disposal areas. Waste-specific constraints may influence selection of a cap material and system design.
- Complete isolation of the site may require the use of a liner system to prevent migration of contaminants into the groundwater.
- Since there exists a confining bedrock layer beneath the site, groundwater diversion can be accomplished through incorporation of a slurry cutoff wall or grout curtain.
- If extensive aquifer contamination exists, it may be necessary to incorporate groundwater flow manipulation techniques to capture, treat, and perhaps reinject groundwater.

3. SOIL CAP SYSTEMS

3.1 **System description**.

3.1.1 Background. Soil cap systems are used to limit in-filtration of precipitation into the waste site and to isolate and contain contaminated areas. Control of infiltration reduces the generation and dispersion of leachate, and plays an important role in the success of an in-situ closure or waste containment strategy. Soil cap systems vary in their function and application, depending on site-specific and waste-specific characteristics. A variety of cap systems are available for application such as native soil covers, multilayer cap systems, soil admixtures, and geotextile fabrics.

The discussion in this section is limited only to the use of cap systems comprised of the following:

(a)   Native soils.
(b)   Soils of low permeability.
(c)   Soil admixtures designed to adjust native soil characteristics.
(d)   Soil stability enhancements such as geotextile fabrics.
(e)   Bio-barrier systems.

Other materials can be placed as part of a cap system over contaminated waste areas, such as synthetic impermeable seals and stabilized soil and waste layers. A discussion of synthetic seals and liners is included in Section 4, while the discussion of stabilization and fixation techniques is included in Section 8.

3.2 **Multilayer cap systems**.

3.2.1 Process description. The multilayer cap system represents a recently developed cover technology that is gaining widespread use in the field as an infiltration control strategy for waste containment or in-place closure. The multilayer cap system performs the basic functions of minimizing infiltration into the waste site; directing and transmitting percolation and gas migration away from the site; and providing a final cover for the site and growth medium for vegetation. A typical multilayer cap system as shown on Figure 15, consists of the following three layers:

(a)   **Uppersoil layer**. A topsoil and native soil layer, typically placed to a depth of about 12-24 inches. This layer serves to support vegetation, provide a cover for the drain layer, and divert surface runoff.

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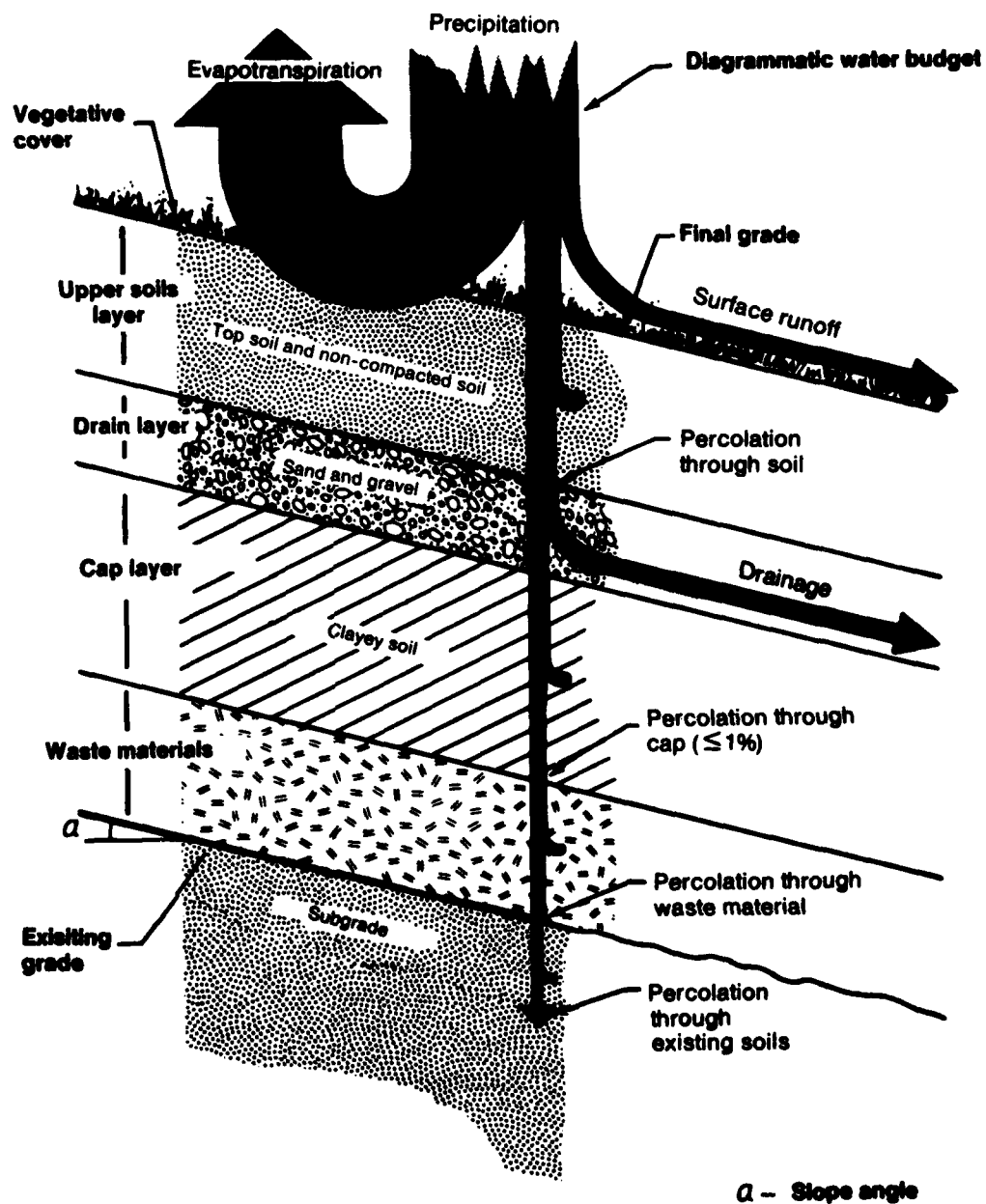
Figure 15. Profile of recommended encapsulation and cover configuration — Canonsburg UMTRAP site.

(b)   Middle drain layer.   A graded layer of porous flow zone
        material (e.g., sand, gravel) to act as a drainage
        medium. This layer is typically placed to a depth of
        about 18 inches.

(c)   Cap layer.   A compacted layer of fine-grained soils of
        low permeability designed to divert infiltration that
        has percolated through the upper soil layer. This cap
        layer is typically placed to depths of about 18-24
        inches.

The successful multilayer cap system incorporates the use of
low permeability materials, such as compacted clays, synthetic
membranes and soil admixtures, to provide a surface seal over
the contaminated area. A zone of rapid permeability materials,
such as graded gravel, aggregate, and drainage geotextile fab-
rics, is typically placed over the cap layer to enhance lateral
movement of water that percolates through the upper soil layer.
The upper soil layer provides the following:

(a)   A soil cover to promote runoff.
(b)   A protective cover for the drain layer.
(c)   A medium for growth of vegetative cover.

The vegetation not only stabilizes the cover system from
possible damage due to water or wind erosion, but also contrib-
utes to moisture loss through evapotranspiration.

Several major advantages of the multilayer cover system as
compared to a standard native soil cover include the following:

(a)   A protective soil layer is placed over the cap layer;
        the cap is not directly exposed to possible damage
        due to weathering, cracking or excessive root pene-
        tration.

(b)   A drain layer serves to divert additional percolating
        water so it does not eventually migrate into the con-
        taminated material.

(c)   Possible slumping of the topsoil and upper soil layers
        is minimized.

3.2.2   Process evaluation methodology.   In the design and
evaluation of a multilayer cap system, an assessment must be
performed of the site-specific waste and area characteristics to
properly match the capping requirements with the proposed cap
system materials. Computer modeling techniques have been devel-
oped as a tool for establishing the design basis for multilayer

cap systems, and field techniques have progressed for providing quality control during material placement and site closure. Figure 15 presents a typical process evaluation methodology that may be followed in the evaluation and design of multilayer cap systems.

The two major aspects of the process evaluation methodology for multilayer cap systems include an assessment of the site-specific characteristics and the design basis for the individual components of the cap system. As Figure 16 indicates, three basic design factors should be included in the evaluation of site-specific characteristics, and the three functional components of the cap system should be evaluated as well. Each of these six design factors, shown below, is briefly discussed in subsequent paragraphs in terms of its application to the evaluation of a multilayer cap system.

(a) Native geological considerations.
(b) Area climatic conditions.
(c) Chemical and physical waste characteristics.
(d) Upper soil layer design basis.
(e) Drain layer design basis.
(f) Cap layer design basis.

3.2.2.1 Native geological considerations. The geology of the immediate area surrounding the contaminated waste area plays an important role in the design and evaluation of a multilayer cap system. Considerations should be given to soil availability, site topography, soil types, geotechnical concerns, and special geological features.

In terms of soil availability, the suitability of native soils to use in the proposed cap system should be established. Each of the cap layers presents individual material requirements, and laboratory and field testing protocols should be followed to ensure that the available soils meet specified requirements. In addition, native soils may be incorporated into a soil admixture layer, where only certain soil types provide appropriate admixing properties.

Site topography should be considered in the evaluation of a multilayer cap system application. The grades maintained throughout the cap layers should be compatible with native topography to enhance positive drainage away from the site. Improper placement of a multilayer cap system and failure to match

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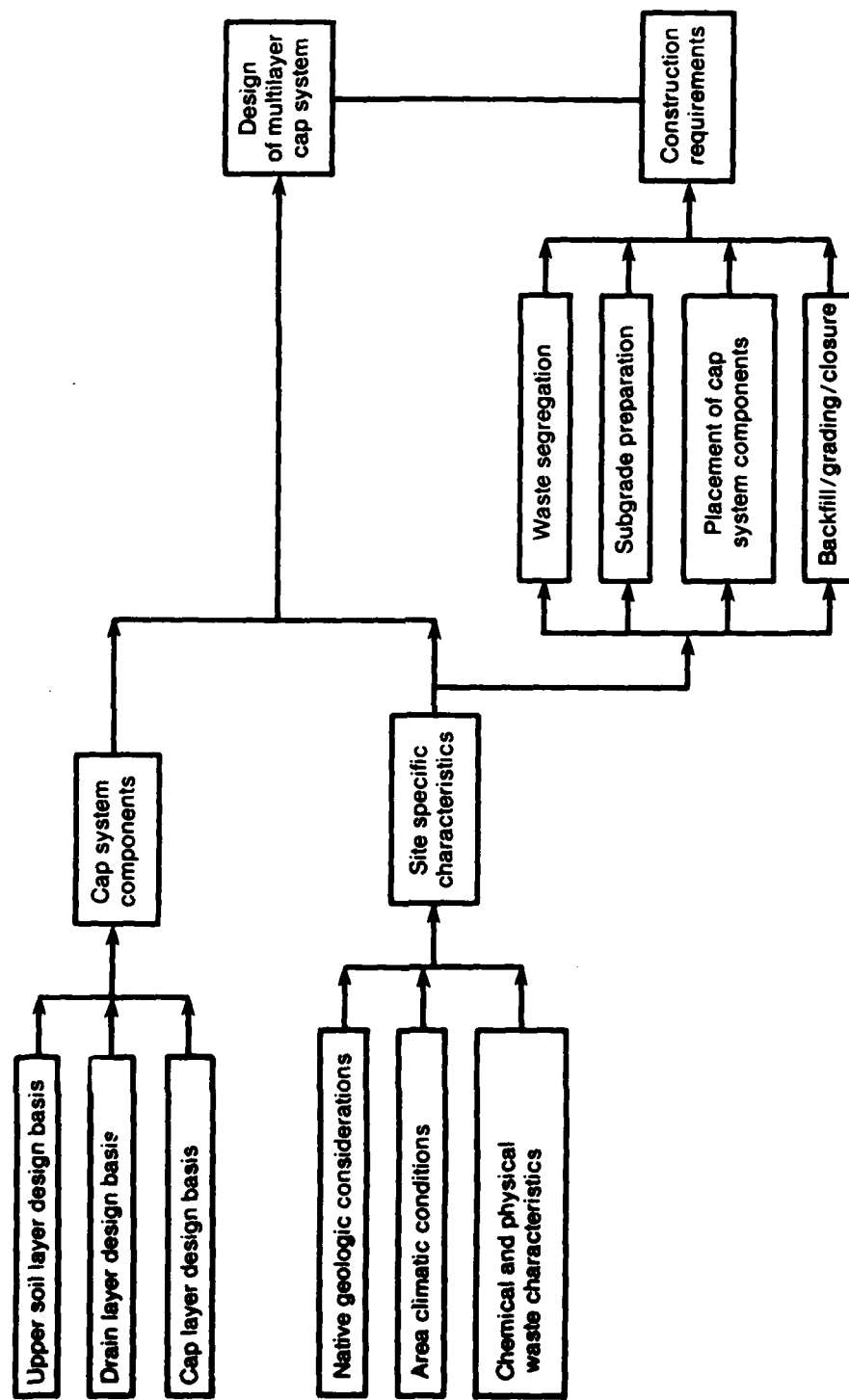
Figure 16. Evaluation methodology for multilayer cap systems.

native conditions may create unusual hydraulic gradients at the site or may increase erosion potential. For these reasons, adequate surface-water diversion techniques (as described in Section 5) should be incorporated into the design of a multilayer cap system.

Geotechnical stability concerns represent another necessary factor in the evaluation of a multilayer cap system. The cap layers place additional loads onto the waste containment area. Subgrade stability is an important consideration, as it must exhibit load-bearing capacities capable of permanently supporting the cap system materials ("static loads"), plus the temporary equipment loads ("live loads") during construction. Other geotechnical characteristics should be assessed for soils that may be used in capping systems. Laboratory and field testing of the soil's physical and chemical properties may be required. Some of the properties that may have to be determined for competing soil types include the following:

(a) Void ratio.
(b) Porosity.
(c) Water content.
(d) Atterberg limits (liquid, plastic, and shrinkage limits).
(e) Soil pH.
(f) Shear resistance.
(g) Compaction.
(h) Permeability.
(i) Shrink/swell behavior.
(j) Grain size distribution.

Finally, an assessment of any site-specific geological features is necessary. The presence of Karst topography and the resultant sinkholes, as well as identification of fault zones, may present significant problems in placement of a cap system. A containment option may not be viable in areas of uncertain bedrock conditions. The placement of a multilayer cap system may not be appropriate in major flood plains. Soil losses from erosion and total washout of the cap system are two significant problems that may result from the use of containment in the flood plain.

3.2.2.2 Area climatic conditions. The climatic conditions encountered at the site represent important considerations for the design and evaluation of a multilayer cap system application. The success or overall failure of individual component layers may be based on the geotechnical responses of the soil materials to area climatic conditions, such as precipitation, temperature, or erosion potential.

Average annual precipitation is a valuable measure of the suitability of cap systems. From an initial design standpoint, sites that encounter extremely low precipitation rates may not require a multilayer cap system approach since a native soil cover may be sufficient (see subsection 3.3 for a discussion of native soil covers). Adequate management of precipitation is an important consideration in avoiding subgrade wick effects and soil dessication in the cap system soils. Major fluctuations in precipitation may create cracking problems and cap failure in the clay layers unless the system design can offset these changes in soil moisture content. Design factors that may be considered potential problems include thickness of the upper soil layer and the characteristics of the material used in the drain layer and cap layer.

Temperature effects play an important role in the assessment of soil cap systems. Certain soils undergo severe expansion in freezing climates (referred to as frost heave), predominantly cohesive soil layers lying in the unsaturated zone which can be influenced by freezing surface temperatures. When frost-susceptible soils are in contact with moisture and are subjected to freezing temperatures, they attract water from below through capillary action and undergo a very large expansion (Lambe, Whitman, 1969). In areas of freeze/thaw climates, the multilayer cap system must be designed and placed to minimize the destructive effects of frost heave conditions. Adequate layer depths must be established to ensure placement of the cap layer below the natural freeze line in the soil profile. In addition, artificial capillary breaks may be installed beneath the cap layer to eliminate the continuous capillary attraction of subsurface water into the frost-susceptible soils. Coarse-grained drainage material or a geotextile fabric can be applied as capillary breaks (see subsection 3.5 for a discussion of geotextile fabrics).

Wind and surface runoff erosional forces can present major potential problems with the application of soil cap systems. In site-specific situations where soil erosion is a major consideration, the USDA Universal Soil Loss Equation (USLE) may provide useful information for comparing different cover soils during

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the design of a cap system (Lutten et al., 1979). The USLE assesses soil loss from the product of six quantitative and qualitative factors as related by the following:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad\qquad (1)$$

Where: A = Average soil loss (tons/year) for the specified time period.
         R = Rainfall-runoff erosion index.
         K = Soil erosion factor.
         L = Slope-length factor.
         S = Slope-steepness factor.
         C = Cover-management factor.
         P = Conservation-supporting practices factor.

3.2.2.3 Chemical and physical waste characteristics. The chemical and physical characteristics of the wastes play an important role in the design and evaluation of the multilayer cap system. Chemical waste compatibility with the cover soils, specifically with reference to the clay cap layer, represents one of the key concerns. Incompatible combinations of wastes and clay types have been shown to reduce the clay's capacity to function as an impermeable boundary (Anderson & Brown, 1980). (See Section 6 for a detailed discussion of bentonite clay compatibility with waste chemicals.) Since the predominant function of a cap system is to significantly reduce site infiltration, clay failures resulting from waste compatibility problems will create major system performance problems.

Biodecomposition of volatile organic wastes creates gas generation concerns that must be addressed in the design of appropriate cap systems. Gas venting measures should be considered as a functional component of a multilayer cap system application for many wastes with a high organic content. Without such control measures, gas can be trapped below the cap layer, gradually altering the subsurface soil grades and potentially reducing the effectiveness of the cap system as designed. Physical waste characteristics, such as the capacity for differential settlement under external loads, the dewatering potentials, and the capacity to form a self-sealing mass, must be evaluated for their effects on in-place closure with a multilayer cap system.

3.2.2.4 Upper soil layer considerations. The upper soil layer of a multilayer cap system is placed to promote surface-water runoff, control erosion, provide a growth for cover vegetation, and protect the drain and cap layers. The upper soil layer typically incorporates clean fill soils, topsoil, and a vegetative cover. Clean fill may be utilized as a general grade-and-fill material to form the basis of the upper soil layer. Topsoil, which is usually placed above clean fill, is typically a loose, uncompacted surface layer of loams for vegetative support. Vegetation serves to reduce the potential for wind and water erosion and helps to establish a naturally fertile and stable soil base. The key to the effectiveness of the upper soil layer is the success in establishing and promoting an effective vegetative cover.

The layer of clean fill soils may range in thickness from a minimum of 18 inches to 3 feet or more. This soil layer must be free of large rocks or stones; roots, branches, or wood; and rubble, debris, or other waste material. The selection of the thickness of this soil fill layer should consider factors such as the following:

(a) Availability of suitable material.
(b) Thickness of topsoil layer.
(c) Possible root penetration depth.
(d) Frost depth.
(e) Climatic conditions and extremes in precipitation.
(f) Possible long-term soil losses.

Topsoil thickness is usually limited to about 6 to 12 inches because of its relatively high cost. If adequate quality topsoil is not available, it may be neccessary to supplement existing soils with fertilizers and conditioners. This supplemental enrichment will provide the general soil composition and macronutrients needed to adequately support vegetation.

Several vegetation characteristics are important to the establishment of a successful cover over the multilayer cap system. These include (JRB Associates, 1982) the following:

(a) Low-growing vegetation.
(b) Limited soil penetration of plant roots.
(c) Rapid germination and development.
(d) Long-term durability (resistance to fire, insects and disease).
(e) Low maintenance requirements.

Slope stability represents an important aspect of the
soil layer. Side slopes should be limited to a maximum ra
3 horizontal to 1 vertical (3:1) to ensure slope stabilit
represents the maximum slope on which vegetation can be
lished and maintained, assuming soils with low erosion po
and adequate moisture-holding capacity. Top surfaces shou
lize a slope of approximately 3 to 5 percent to promote d
and encourage runoff.

Vegetation may be used as part of a long-term site r
tion project or on a temporary basis as a surface stab
agent for intermediate covers. Long-term vegetative sta
tion typically involves planting grasses, legumes, and
shrubs, while a short-term seasonal cover is limited usu
grasses. This subsection is concerned primarily with the
term applications of vegetation as a surface cover for tl
tilayer cap system. For these applications, grasses and .
are commonly used (see Table 4 for a listing of vegetatiol
acteristics,. The following factors should be considered
evaluation of vegetative covers:

(a)   Selection of a suitable plant species.
(b)   Seedbed preparation.
(c)   .Vegetation seeding/planting.
(d)   Mulching/chemical enrichment of soil.
(e)   Fertilization and maintenance.

3.2.2.5 Drain layer considerations. The second func
component of the multilayer cap system is the drain layer
layer is "sandwiched" between the upper soil layer on t
the cap layer underneath. The drain layer consists of a
tively high permeability material to provide a lateral dr
path for water that percolates through the upper soil laye
drain layer must provide rapid transmission of the wate
will tend to collect (perch) on the cap layer. Drain laye
formance can be modeled using the Hydrological Simulati
Solid Waste Disposal Sites (HSSWDS) computer simulation
developed for the U.S. EPA (Moore, 1980). From the mode
required drain layer thickness can be evaluated. The
thickness requirement is a function of the following desiq
siderations:

(a)   Annual infiltration rate.
(b)   Drain layer length.
(c)   Permeability of drain layer material.
(d)   Drain layer slope.

TABLE 4. CHARACTERISTICS OF GRASSES AND LEGUMES
COMMONLY USED FOR REVEGETATION

| | Season | | | Site suitability | | | Growth habit[a] | Optimum pH range |
	Cool	Warm	Dry	Well drained	Moderately drained	Poorly drained		
Grasses								
Bahia grass		X	X	X	X		P	4.5 - 7.5
Barley	X			X	X		A	5.5 - 7.8
Bermuda grass		X	X	X	X		P	5.5 - 7.5
Blue grass, Canada	X		X	X	X		P	4.5 - 7.5
Blue grass, Kentucky	X			X	X		P	5.5 - 7.0
Bluestem, big		X		X	X		P	5.0 - 7.5
Brome grass, field	X			X	X		A	6.0 - 7.0
Brome grass, smooth	X		X	X	X		P	5.5 - 8.0
Buffalo grass		X			X		P	6.5 - 8.0
Canary grass, reed	X		X	X	X	X	P	5.0 - 7.5
Deer tongue		X	X	X	X	X	P	3.8 - 5.0
Fescue, tail	X			X	X		P	5.0 - 8.0
Grama, blue		X	X	X	X		P	6.0 - 8.5
Indian grass		X			X		P	5.5 - 7.5
Love grass, sand		X		X			P	6.0 - 7.5
Love grass, weeping		X	X	X	X		P	4.5 - 8.0
Oats	X		X	X			A	5.5 - 7.0
Orchard grass	X		X	X	X		P	5.0 - 7.5
Red top	X		X	X	X	X	P	4.0 - 7.5
Rye grass	X		X	X		X	A,P	5.5 - 7.5
Switch grass		X	X	X			P	5.0 - 7.5
Timothy	X			XX	X	X	P	4.5 - 8.0
Wheat grass, tall	X		X	X	X	X	P	6.0 - 8.0
Wheat grass, western	X		X	X	X	X	P	4.5 - 7.0
Legumes								
Alfalfa	X		X	X			P	6.5 - 7.5
Clover, alsike	X		X	X	X	X	P	6.0 - 7.0
Lespedeza, common			X	X	X		A	5.0 - 6.0
Lespedeza, sericea		X	X	X	X		P	5.0 - 7.0
Sweet clover, white or yellow	X		X	X	X		B	6.0 - 8.0
Trefoil, birdsfoot	X		X	X	X		P	5.0 - 7.0
Vetch, crown	X		X	X	X		P	5.5 - 7.5
Vetch, harry	X		X	X	X		A	5.0 - 7.5

[a]A = annual, B = biennial, P = perennial (Source: EPA, 1976)

The modeling technique may be graphically portrayed as shown on Figure 17 (Moore, 1980). The figure shows a drain layer of thickness, d, overlying a low permeability material layer (cap layer is discussed in subsection 3.2.2.6). The drain layer extends over a horizontal distance of length, L, and is placed at a slope from horizonal of angle, a . Percolating water impinges on the drain layer at an annual infiltration rate, e, and can move through the layer at the drainage materials' saturated permeability rate, K_S. It is assumed that the percolation rate is constant with respect to time, which is valid, since seepage fluxes do not change rapidly.

The limiting case for the evaluation is the condition when $a = 0$ (the drain layer has a horizontal or zero slope). The height of the saturated water surface within the drain layer for this limiting case is given by the following relationship (Moore, 1980):

$$h = \left(\frac{e}{K_S} (L-X) \ X \right)^{1/2} \tag{2}$$

Where: h = Water height (m).
e = Infiltration rate (cm/sec).
K_S = Permeability rate (cm/sec).
L = Drain layer length, or length between drain pipes (m).
X = Horizontal point in question (m).

The maximum height of the water in the drain layer, h_{max} occurs at the midpoint, $x = L/2$, and is given as:

$$h_{max} = \left(\frac{eL^2}{4K_S} \right)^{1/2} \tag{3}$$

In situations other than the trival limiting case of a horizontal rain layer, the layer slope angle will become a factor in the evaluation ($a > 0$), and flow will accelerate toward the collector system. Having a drain layer slope greater than zero is critical to the function of the multilayer cap system, since it allows water to drain in a finite amount of time. If $a = 0$, the drainage time is infinitely long, and for the case of a sloped drain layer, ($a > 0$), h_{max} is given as (Moore, 1980):

$$h_{max} = \frac{L \sqrt{c}}{2} \ \frac{\tan^2 a}{c} + 1 - \frac{\tan a}{c} \ \sqrt{\tan^2 a + c} \tag{4}$$

Where: c = Flow rate ratio of $\frac{e}{KS}$

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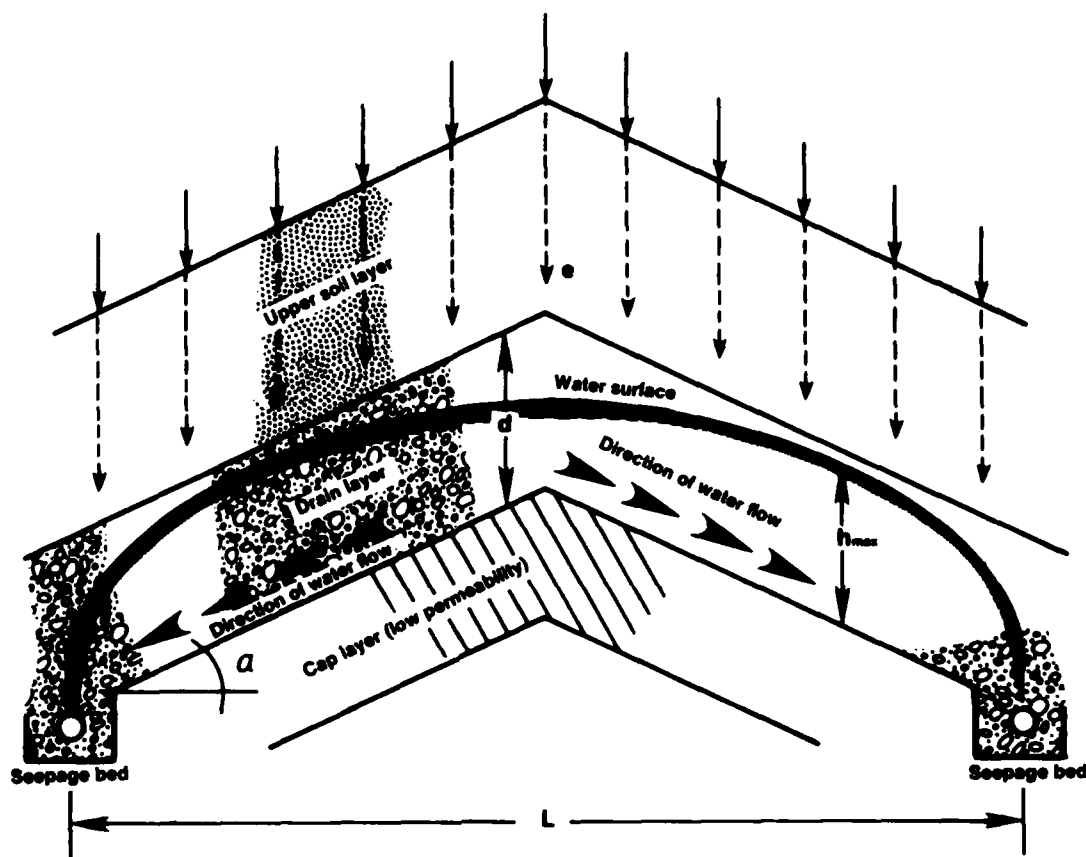
h_{max} — Maximum height of water standing in the drain layer

d — Drain layer thickness

L — Distance between opposing laterals or seepage beds

e — Rate of water flow impinging on drain layer, equal to percolation rate

a — Slope angle

Source: Moore, 1980

Figure 17. Diagram of assumed water surface profile in drain layer.

To evaluate the effectiveness of the drain layer, a sensitivity analysis should be performed, examining the effects of infiltration rate, drainage length and slope, and saturated permeability on the maximum standing water height. As a general rule, drain thickness requirements increase as a function of an increase in annual percolation rate and a decrease in drain layer material permeability. Other parameters being equal, drain layer thickness requirements decrease as a function of increasing slope. The most critical parameter to an effective drain layer is saturated material permeability.

In addition to calculating the required drain layer thickness, an equally important factor is drain layer efficiency. Drain efficiency is a measure of the drain's capacity to divert laterally the water that is percolating vertically. The drain layer efficiency is a function of particle size, drain slope, and drain length. The approach for estimating drain layer efficiency is based on saturated Darcy flow in both the drain layer and cap layer (Moore, 1980). This approach assumes that the cap layer is composed of a material (e.g., clay) that is not completely impermeable. Figure 18 shows a graphical representation of the assumed geometry. This approach postulates that at some initial time a rectangular slug of liquid is placed on the saturated cap layer to a depth, h_0. The liquid flows both horizontally along the slope of the system, and vertically into the cap layer. The fraction of liquid moving into the collector drain system at time, t, is given as follows (Moore, 1980):

$$\frac{S}{S_o} = 1 - \frac{t}{t_1} \tag{5}$$

and the fraction of liquid seeping into the cap layer is given by:

$$\frac{h}{h_o} = \left(1 + \frac{d}{h_o \cos a}\right) e^{-ct/t_1} - \frac{d}{h_o \cos a}, \text{ for } 0 \le t \le t_1, \tag{6}$$

Where:

$$t_1 = \frac{S_o}{K_{sl} \sin a}$$
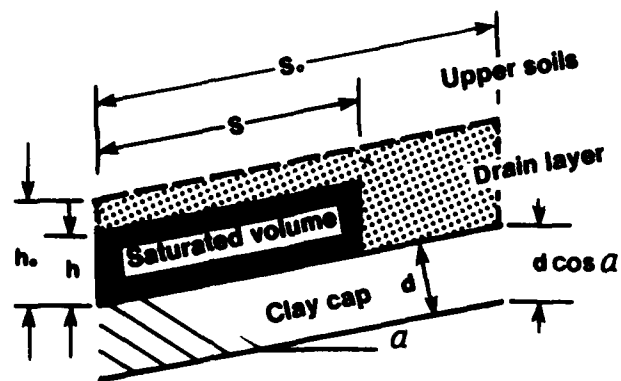
a Geometry for calculating efficiency of drain layer
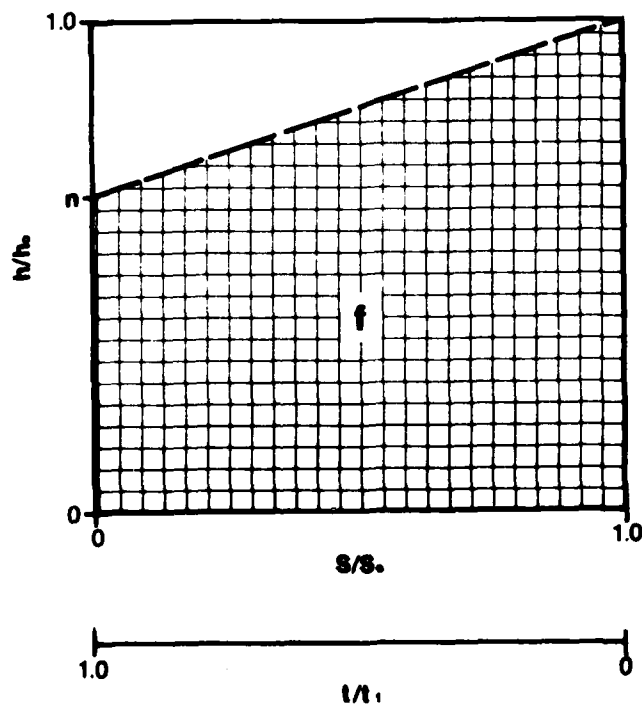
b Diagram for computing efficiency of drain layer

Source: Moore, 1980

Figure 18. Assumed geometry for computing drain layer efficiency.

$$c = \left(\frac{S_o}{d}\right)\left(\frac{K_{s2}}{K_{s1}}\right)\cot \alpha$$

and

S = Length of saturated volume at time, t (cm).
h = Thickness of saturated volume at time, t (cm).
S_o = Initial length of saturated volume = L/2 secant (cm).
h_o = Initial thickness of saturated volume (cm).
K_{s1} = Saturated permeability of the material above the cap layer (cm/sec).
K_{s2} = Saturated permeability of the cap layer (cm/sec).
α = Slope angle of the system (degrees).
d = Thickness of the cap layer (cm).

The efficiency of the drain layer can be determined with reference to Figure 18 which plots h/h_o versus S/S_o and t/t_1. Equations 5 and 6 can be solved parametrically in t/t_1, to yield the line shown on the figure. (The line is actually a curve, however, for practical cap and drain layer configurations it can be approximated as a straight line.) In this case, the efficiency of the system is given by the area labelled "f." This area is most easily determined by calculating the value of h/h_o when t/t_1 = 1.0 (or S/S_o = 0). The term h/h_o is set equal to n and can be obtained by solving equation 6 with t/t_1 = 1.0.

$$n = \left(1 + \frac{d}{h_o \cos \alpha}\right)e^{-c} - \frac{d}{h_o \cos \alpha} \tag{7}$$

The value of n can be either positive or negative, however, most efficient designs will have n > o. The efficiency is given by either:

$$f = \frac{1 + n}{2} \qquad \text{for } n > o \tag{8}$$

or

$$f = \frac{1}{2 (1-n)} \qquad \text{for } n < o \tag{9}$$

Thus, the "efficiency" varies from 0 to 1.0.

The quantity of liquid draining out of the system is given by:

Amount collected in drains = $f \times h_o$ and the quantity of liquid seeping into the cap layer is given by:

Amount seeping into liner = $(1-f) \times h_o$.

3.2.2.6 Cap layer considerations. A major component of the multilayer cap system is the impermeable cap layer that underlays the drain layer. The term "impermeable" is a misnomer for soil caps, since no native soil can act as a complete barrier against percolation. Synthetic membranes and seals more closely exhibit the impermeability designation. However, cap layer permeability rates may be extremely low (in the range of 10^{-6} - 10^{-8} cm/sec), and in essence they are often referred to as "impermeable." The cap layer represents the zone that significantly limits the movement of percolating water into the contaminated waste area. The cap layer truly provides the containment function of the multilayer cap system.

The cap layer may be constructed using the following materials:

(a)   A native low permeability soil.
(b)   A soil admixture.
(c)   A synthetic membrane or seal.
(d)   A low permeability layer constructed of fixed, stabilized material.

The cap layer may be constructed either of one layer of low permeability compacted soil or admixture, or of two compacted soil layers consisting of one layer of base material overlain by a second layer of low permeabilty soil or admixture material. The decision for utilizing one layer or two in the cap should consider material availability cost, and the characteristics of the underlying waste material. All water that permeates the cap layer will, in time, ultimately percolate downward through the waste material. During the time that water permeates the cap, the soil moisture content will increase. From the modeling techniques of HSSWDS (Moore, 1980), this wetting process can be evaluated to determine the time required to completely permeate the cap layer.

Describing the permeability of cap materials such as clay is more involved than describing flow through noncohesive soils, such as sand and gravel, which would be used in the drain layer. Clays have gravitational attractive properties and exert capillary forces that complicate the mathematics of flow calculations. After solving linear differential equations for flow through clay layers, the following relationship can be used to give the cumulative amount of water entering the clay barrier soils at a given time, t (Moore, 1980),

$$M_t = 2 \left(\Theta_s - \Theta_1 \right) \sqrt{\frac{Dt}{\pi}} \qquad (10)$$

and the quantity of liquid required to saturate the barrier to a depth, d, is given as:

$$M_t = 2 \left(\Theta_s - \Theta_1 \right) d \qquad (11)$$

Where:

M_t = Required liquid quantity (cm).
Θ_s = Saturated soil moisture content (percent).
Θ_i = Initial soil moisture content (percent).
D = Soil diffusivity (sq cm/sec).
t = Time (sec).
d = Soil depth (cm).

Equating the two relationships, an approximation can be made of the time required for water to completely permeate a clay cap. This time, calculated as follows, relates to the delay time that the clay layer provides in preventing percolation from entering the waste area.

$$t = \frac{\pi d^2}{4D} \qquad (12)$$

3.2.3 Materials verification. One of the first steps in the performance verification process is materials verification. If the materials do not meet the desired specifications, a component in the in-situ closure design may be subject to failure. This type of materials test can generally be performed in a soils laboratory and may typically include the parameters shown in Table 5.

3.3 Native soil covers.

3.3.1 Process description. Certain geological and climatic situations and certain waste characteristics may allow the use of a single-layer cap system comprised of native soils. In climates with evaporation rates that are greater than precipitation, and in locations where low permeability soils are readily available, the use of a multilayer cap system may not be necessary. In addition, a higher cost multilayer cover may not be required for waste areas that are not highly leachable, stabilized, or of a low hazard/toxicity level. For example, the final cover for an area where the waste has been fixed or chemically stabilized may be a single layer of soil. The use of native soil covers has its basis with the disposal of municipal solid wastes in sanitary landfills. For years, daily soil covers and final soil covers have been applied for the closure of solid waste cells at sanitary landfills.

TABLE 5.   TYPICAL MATERIALS TESTING PARAMETERS

Component	Characteristics	Test protocol
Upper soil layer material		
Topsoil	1. Organic content 2. pH 3. Suitability-clean	1. Soil classification. 2. Field testing procedure. 3. Visual -- free from foreign matter and other debris.
Soil fill	1. Low course fragments	1. Sieve analysis AASHTO T-27.
	2. Suitability-clean	2. Visual -- free from rocks, stones, debris, waste material, roots, sticks.
	3. Compactable	3. Density at optimum moisture -- AASHTO T-99.
Drain layer material	1. Soil type	1. Soil classification.
	2. Allow rapid water movement.	2. Sieve analysis -- permeability.
	3. Suitability-clean	3. Visual -- free from plants, roots, stones, debris.
Cap layer (clayey soil)	1. Workability	1. Liquid limit -- AASHTO T-89. Plastic limit -- AASHTO T-90.
	2. Soil type	2. Sieve analysis -- AASHTO F-11 and AASHTO F-27.
	3. Restrict water movement	3. Permeability.
	4. Compactable	4. Maximum density at optimum moisture -- AASHTO T-180.
	5. Suitability-clean	5. Visual -- free from stones, roots, plants, debris.

Single-layer native soil covers simply provide a physical barrier against human contact with the contaminated area and provide a mechanism for improved surface runoff. Beyond the evapotranspiration and surface management controls achieved through regrading, placement of a native soil cover, and revegetation, only slight reductions in the rate of subsurface infiltration are gained. The level of subsurface environmental control achieved through native soil capping is not as great as that of a multilayer cap system (discussion of the multilayer cap system is included in subsection 3.2).

Native soil covers should only be considered when complete waste isolation is not required and a significant reduction in site infiltration is not a primary concern. In dry climates where evaporation is greater than annual rainfall, the amount of infiltration is generally not a major concern and infiltration controls would only apply on a seasonal or storm event basis. Nonleachable waste areas can be appropriately closed with native soil covers. Subsurface percolation can pass through the insoluble waste, but little or no contaminated leachate would be generated. In the situation where waste processing or solidification is incorporated into a waste containment strategy, native soil covers may be a satisfactory capping approach.

3.3.2 Process evaluation methodology. In the design and evaluation of native soil covers, consideration should be given to soil layer thickness and soil type. Cover soil thickness should be sufficient to protect the integrity of the cover from possible damage from frost effects (as described within subsection 3.2.2.2), and should be capable of supporting vegetation. Upper soils should support plant growth, and care should be given to root penetration depths. Proper selection of vegetation for shallow root penetration should be a part of the design of native soil covers.

3.3.3 Materials verification. The specific application of a native soil cover system will establish the materials verification program. If infiltration reduction is not a primary objective, then the native soil cover will be serving more as a physical barrier over the contaminated area and a medium for vegetative growth. This objective could be met by a clean soil fill material. If infiltration reduction is a primary objective, the native soil cover will more closely resemble a clayey soil material. In both cases a topsoil layer may be recommended to help establish vegetative growth.

The material characteristics and testing parameters for these types of soils are listed in Table 5, and will apply in the case of native soil covers.

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3.4 Soil/bentonite admixtures.

3.4.1 Process description. A low permeability soil/bento-
nite admixture can be placed as the cap layer in the multilayer
cap system or as a single layer cap system. As a proven capping
technique in waste management, which is gaining acceptance in
field construction applications, soil/bentonite admixtures will
be discussed briefly in this subsection. These admixtures incor-
porate a combination of natural and processed bentonite for use
in many cap system applications. Soil/bentonite admixtures can
replace a natural low permeability soil (e.g., clay) layer when
appropriate soil deposits are not available or cannot be used
in a cost-effective manner.

The process typically incorporates a geotechnical assessment
of the available soils for use in the admixture and a determin-
ation of the necessary bentonite application rate to achieve the
desired cap effectiveness. The bentonite is placed and "admixed"
with the soils, and the mixture is uniformly spread and compact-
ed. The bentonite, once hydrated to the optimum moisture con-
tent, swells to fill the void spaces within the soil layer, and
an effective seal is achieved to control site infiltration.

Bentonite contains practically the same chemical constitu-
ents as other clay substances, but its unique molecular struc-
ture accounts for its ability to absorb many times its own
weight in water. Bentonites swell significantly in the process
with increases at full saturation ranging up to 15 times their
original dry bulk (American Colloid literature). This swelling
characteristic may create problems in contaminated waste areas.
In the presence of certain chemicals, natural bentonites may un-
dergo significant shrinkage characteristics with absorbed inter-
stitial water being driven from the expanded soils. This has the
net adverse effect of actually increasing the permeability of
the admixture. (A detailed discussion of chemical compatibility
with clay is discussed in Section 6.) To counteract this physi-
cal and chemical phenomenon, processed bentonites have been mar-
keted with certain additives to reduce the potential for chemi-
cal attack for soil/bentonite applications with contaminated
wastes.

3.4.2 Process evaluation methodology. The design and eval-
uation of soil/bentonite admixtures incorporate the two basic
steps of appropriate bentonite admixture selection and place-
ment of the soil/bentonite layer. The final result of the eval-
uation is the determination of the applicability of a particular
soil/bentonite admixture for a cap system.

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3.4.2.1 Selection of bentonite admixture. To effectively assess the applicability of soil/bentonite surface seals or caps, the designer must establish the basic requirements of the system and match the selected admixture with these requirements. Three factors should be a part of this bentonite admixture selection process. These include the following:

(a) Establish waste area characteristics and compatibility.
(b) Assess site-specific geotechnical characteristics.
(c) Determine required bentonite application rates.

The compatibility of the soil/bentonite layer with the contained wastes represents a key issue in the evaluation of such a system. High levels of dissolved salts and other chemical contaminants may have an adverse effect on the swelling and water-impeding properties of bentonite soils (American Colloid literature). Chemically-treated sodium-based bentonites have been laboratory-tested for their compatibility with certain chemicals. Although analyses have not been performed on all of the chemical types that could be found in various waste materials, some of the results available at present indicate that a chemically-treated or processed bentonite is capable of maintaining an effective seal in the presence of contaminated wastes (American Colloid literature). These contaminant-resistant bentonites may provide acceptable application to a soil/bentonite admixture. Bentonite vendors are in the process of establishing a "shopping list" of compatible and incompatible wastes, similar to those that have been developed for synthetic liner materials.

A second important factor in assessing soil/bentonite admixtures is consideration of geotechnical characteristics. An evaluation of the soil for use in the admixture must be a part of the cap layer design. Some important geotechnical characteristics to be assessed include the following:

(a) Soil type.
(b) Porosity and void ratio.
(c) Pore size distribution and gradation.
(d) Moisture content.
(e) Atterberg indices.

In general, the fine-grained soils have better applicability with bentonite admixtures since their pore size openings are smaller and their inherent permeability rates are less than coarse-grained soils (WESTON, 1982). Clay soils, however, are an exception. The cohesive nature of clays, in general, makes

admixing operations difficult. Ideal soils tend to be inorganic silts and poorly-graded sand/silt mixtures. As in the evaluation of soil materials for other containment applications, such as the multilayer cap system and native soil covers (discussed in the previous subsections 3.2 and 3.3, respectively), use of an established soil classification system should be incorporated.

From an assessment of waste compatibility and geotechnical characteristics, the appropriate bentonite type and application rate can be determined for the particular situation. For most waste management applications, a chemically-treated, semigranular, contaminant-resistant bentonite should be selected. Documentation and certification of the contamination resistance of the bentonite admixture should be established. Application rates (generally referenced in pounds bentonite applied per square foot of soil) are dependent on the soil to be admixed and the degree of infiltration control desired. To achieve low permeability rates necessary for in-place containment capping applications, bentonite application rates must be sufficient to adequately seal off the soil pore spaces. Typical admixture layer depths may range from 6-24 inches, and typical bentonite application rates may range from 2-10 pounds per square foot (lb/sq ft) of admixture layer (American Colloid literature; WESTON, 1982).

To confirm the compatibility issues and application rates, it may be advisable to perform bench-scale testing. These services are offered by various vendors and soil testing laboratories.

3.4.2.2 Placement of bentonite admixture. Soil/bentonite admixing procedures have evolved as the construction applications have grown. Proper design of the soil/bentonite cap layer would not be complete without assessing potential implementation and construction constraints. Subgrade soil preparation must be performed and a decision about the bentonite placement method should be made. Soil/bentonite admixing may be accomplished through either manual or mechanical methods. Table 6 shows a brief comparison between construction steps for the two admixture approaches. Manual placement and admixing procedures were utilized during the early soil/bentonite applications. As construction techniques have expanded, mechanical spreading and discing techniques have been incorporated to enhance process control. The greatest level of quality control can be achieved through bulk admixing of the soil and bentonite in a pugmill or equivalent equipment type, and mechanical placement of the admixture layer using an asphalt paving or equivalent equipment type.

TABLE 6. SOIL/BENTONITE ADMIXTURE APPROACHES

| Step | Admixture approach | |
	Manual	Mechanica
Subgrade preparation	Grade soils	Grade soils
Bentonite delivery	Bagged bentonite on flatbed trucks; place on established soil mixture grid system.	Bulk truck or car with conv(
Soil conditioning	Hand-held hose or watering truck to adjust soil moisture.	Watering truck adjust soil mc ture.
Spreading	Open bentonite bags and rake spread onto surface.	Fertilizer or lime spreader, pugmill mixing bentonite and to be spread w asphalt-type e ment.
Discing	Rototiller or rotary tiller.	Agricultural d or spring-toot harrow; discin not necessary pugmill mixing technique.
Compaction	Roller with vibrator.	Roller with vi brator.
Top cover placement	Place fill or next cap system layer.	Place fill or cap system lay

3.5 Geotextile fabrics.

3.5.1 Process description. Over the past few years, the use of synthetic fabrics has expanded to widespread acceptance throughout the construction industry. Synthetic fabrics have been used in construction for road enforcement, separation of materials, erosion control systems, and flexible forms. These construction applications place specific emphasis on improvement of subgrade conditions common to heavy construction and geotechnical engineering problems. Through the manufacture of impermeable synthetic fabrics, the category of impermeable liner materials has emerged (synthetic liner materials are discussed in detail in Section 4 of this document). This subsection describes and evaluates the use of synthetic construction fabrics (geotextile fabrics or geotextiles) as possible components within an in-situ containment system. It is not likely that geotextiles by themselves can serve as a closure alternative but can be used as a component with a multilayer or single layer cover system.

The majority of the construction geotextiles that are currently in use incorporate three synthetic materials in their production, i.e., nylon, polyester, and polypropylene (olefin) (Koerner, 1980). Geotextile fabrics may be characterized as either woven or nonwoven, according to the production technique. Woven fabrics incorporate the techniques developed within the clothing and textiles industry to produce a synthetic cloth of specific weave. Nonwoven fabrics comprise the bulk of the construction geotextile industry, and are composed of textile fibers bonded together by resins, other bonding agents, or mechanical processing. The manufacture of nonwoven fabrics generally includes fiber preparation, web formation, web bonding, and post treatment to produce a smooth uniform fabric mat.

Many manufacturing processes exist for production of nonwoven geotextile fabrics, but the majority are manufactured through needle-punched or spun-bonded processes. The needle-punched process incorporates specially designed needles to trap the fibrous web material between a bed plate and a stripper plate, as shown on Figure 19. The needles mechanically bond the individual fibers by punching through the fiber web and reorienting the fiber positions. Needle-punched fabrics generally retain bulk characteristics while exhibiting high densities, and typically are used in construction as filter media or roadbed base material.

Production technique 1: Needle-punched process
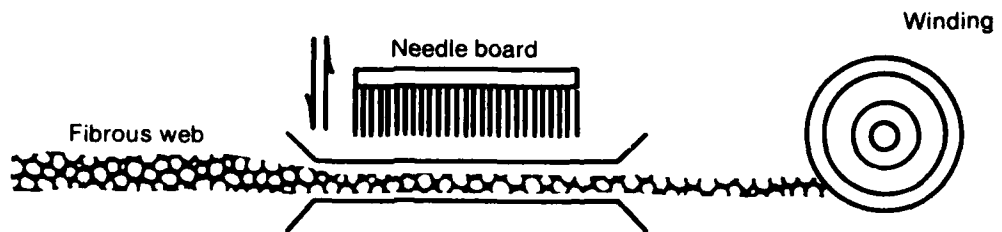
Production technique 2: Spun-bonded process
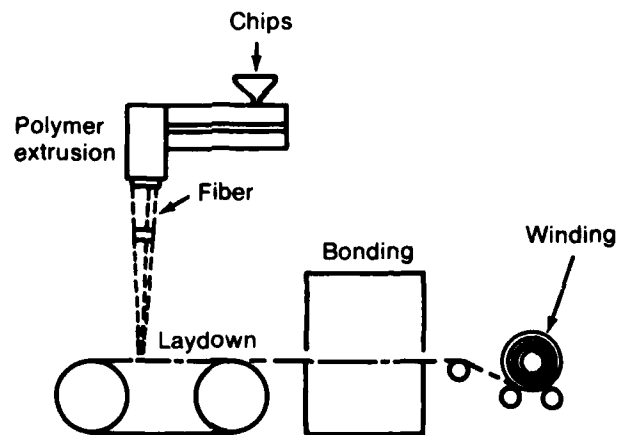
Adapted from INDA, Association of Nonwoven Fabrics Industry.

**Figure 19.   Typical production techniques
                for nonwoven geotextile fabrics.**

The spun-bonded process, as shown on Figure 19, produces a continuous fabric of extruded fibers. Polymers are placed into an extruder where continuous fibers are produced and forced through a series of spinnerets. Once cooled, the fiber filaments undergo a lay-down process on a moving conveyor to form a continuous web exhibiting the desired fiber orientation. Thermal, mechanical, or chemical treatment is used to bond the fiber web, producing the final fabric blanket. A wide range of fabric characteristics are attained by controlling the various spun-bonded process elements. Because of continuous fiber production, spun-bonded fabrics exhibit high performance and low-weight characteristics. Their uses are varied throughout the construction industry.

Geotextile fabrics are rapidly becoming commonplace in the construction industry. The number and type of appropriate applications are continuously expanding because of rising labor costs and increasing problems with locally available soil materials. Construction geotextile fabrics may be applied to serve four basic functions for a waste containment strategy, as follows:

(a)   Separation.
(b)   Reinforcement.
(c)   Drainage.
(d)   Erosion control.

3.5.1.1   Separation applications.   One of the functions that geotextile fabrics can provide to a containment strategy is the separation of dissimilar material layers to enhance the geotechnical properties of the subgrade soils. A fabric boundary may be placed between two differing soil layers to eliminate the migration and loss of soil fines into underlying coarse-grained soils. For example, a geotextile may be used in a multilayer cover system and placed between the drain layer and the upper soil layer. The geotextile will prevent soil fines in one upper soil layer from migrating into the drain layer, thereby, resulting in clogging.

Separation geotextile fabrics can reduce the effects of settlement, frost action, and roadbed deterioration, and may enhance the permeability and strength characteristics of the subgrade soils. Geotextiles have been successfully applied to separate dissimilar zoned sections within embankments and dams to provide a separation boundary for temporary placement of stone or other materials (as surcharge loads for soft soils or downstream berms for unstable slopes), and to separate frost-susceptible soils into distinct layers, reducing capillary flow

continuity. These types of uses may have application as components within the overall construction scope of an in-situ closure project.

3.5.1.2 Reinforcement. The use of construction geotextiles for the reinforcement of unstable subgrade soils serves as a major functional application to waste containment. The placement of the geotextile decreases the effective unit vertical stress of an applied load. The fabric decreases the level of stress encountered in the foundation soil by creating a pathway to increase the horizontal shear stresses. Applied loads place the fabric in tension, which spreads the loads over larger areas and decreases its intensity. Through this reinforcement, the stability of weak subgrade soils is improved, the degree of soil settlements is decreased, and the likelihood of subgrade failure is reduced.

Reinforcing geotextiles have been applied successfully in the construction of temporary site access roads above marsh and swamp areas, construction above unstable permafrost soils, and the construction of fabric walls. Geotextile fabrics have been used in situations of marginal to poor soil characteristics where subgrade removal is necessary. Geotextiles have been used to reinforce and increase the stability of embankments and dams and as containment for soils that would normally spread laterally under applied loads.

3.5.1.3 Drainage applications. The control of subsurface drainage can present major design concerns in the consideration of a waste containment strategy. Sand, gravel, or aggregate flow zone layers are typically placed as part of a multilayer cap system. Construction geotextiles can be well-suited to the control of subsurface drainage. Drainage fabrics can be installed in place of or as part of a soil drain layer in many acceptable and economical applications.

Subsurface drainage theory, developed by Terzaghi, incorporates successively finer or coarser soil layers to prevent migration of soil while conducting flowing water (Lambe, Whitman, 1969). Placement of soil cap layers is expensive and labor-intensive and may require large quantities of different granular soil types. The use of drainage geotextiles in place of these graded filters can more economically prevent the migration of soil fines. Geotextiles can be used to reduce required subgrade excavations, to decrease the probability of trench cave-ins, and reduce construction times. Drainage geotextiles have been applied successfully in underdrain systems, behind retaining walls, and as fabric drains to accelerate settlement.

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3.5.1.4 Erosion control. Construction geotextiles can be readily applied to control surface and subsurface soil erosion. In many situations an erosion control geotextile acts as both a separation layer and a drainage layer. Erosion control fabrics can be placed beneath a stone layer, gabions or riprap acting as a boundary layer to protect slopes adjacent to flowing water. Fabrics can protect water and sewer outfalls against erosion, and can be used as silt fencing to prevent wind and water erosion of soil fines.

3.5.2 Process evaluation methodology. The methodology for selection of a geotextile for use within the design of an in-situ containment project requires evaluation of several primary elements. These include the following:

(a) Desired application.
(b) Site-specific conditions.
(c) Geotextile properties.

Once the geotextile is selected other factors must be investigated to specify construction requirements and performance verification/testing. This decision methodology is depicted on Figure 20 and will be discussed further in the subsections that follow.

3.5.2.1 Assessment of site conditions and potential applications. A necessary aspect in the selection of an appropriate construction geotextile involves matching the site-specific geotechnical conditions and desired applications with candidate fabrics. Three basic geotechnical site-specific conditions form the basis of this assessment. Each addresses a potential concern of a particular in-situ waste containment strategy, and incorporates specific geotechnical design parameters. These site-specific geotechnical conditions are briefly discussed in this subsection and include the following:

(a) Subgrade stability.
(b) Subgrade drainage.
(c) Soil erosion.
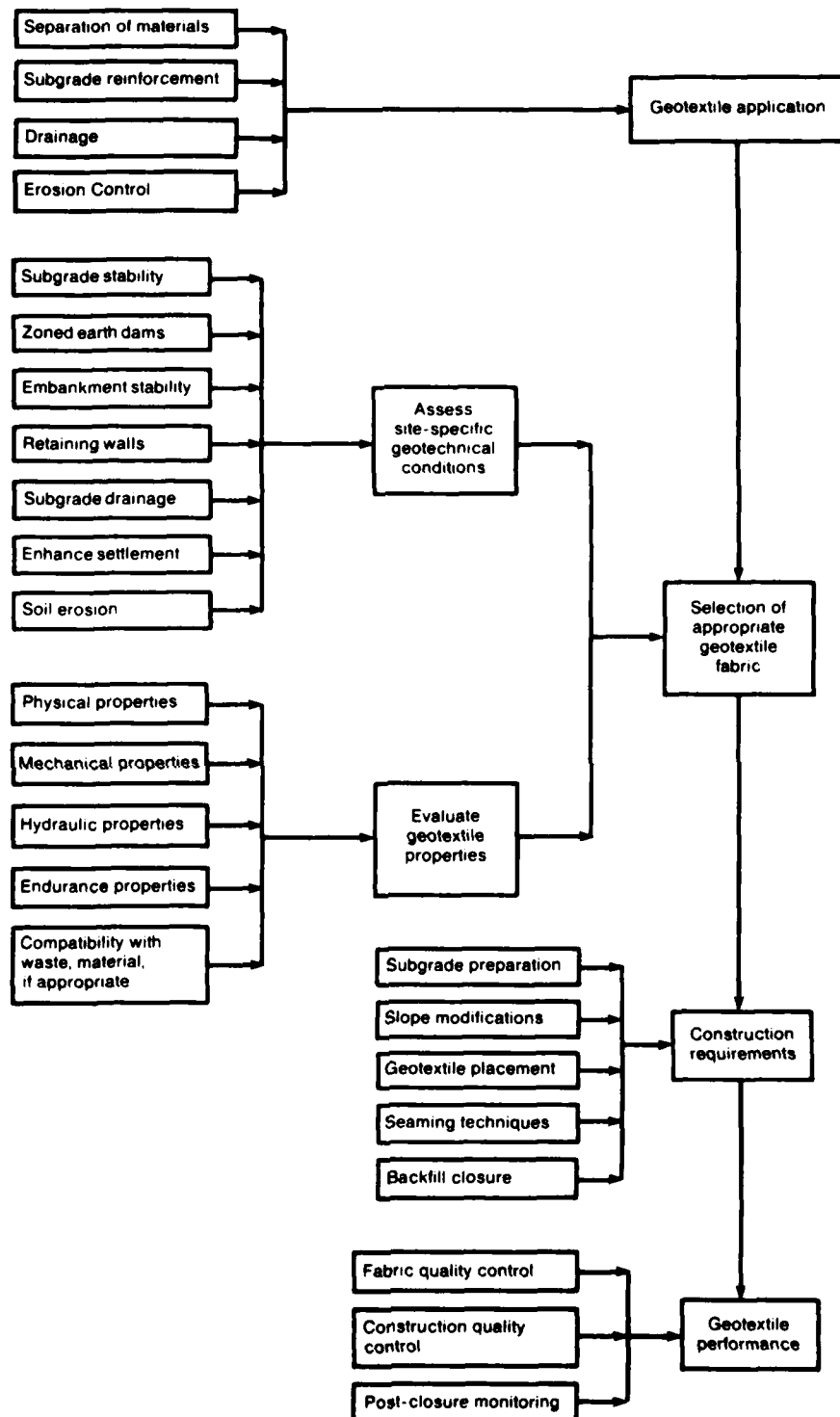
Figure 20. Methodology for selection of geotextile fabrics.

Subgrade stability - For application of geotextiles to reinforce weak or unstable subgrades, designers typically employ the Boussinesq Theory. The Boussinesq equation, as follows, assesses the stress mobilization of vertical loads throughout a radial distribution from the application point of the load (Taylor, 1948).

$$T_r = \frac{P}{2\pi z^2} \left[3 \sin^2\theta \cos^3\theta - \frac{(1-2\mu)\cos}{1 + \cos\theta} \right]^2 \theta \qquad (13)$$

Where:
- T_r = Radial stress.
- P = Applied surface load.
- Z = Depth to point considered.
- θ = Angle from load application to point considered.
- μ = Poisson's ratio for the soil.

Directly beneath the surface load, the subgrade material is placed in tension. Tensile stresses are maximum near the surface and decrease with depth. Weak or unstable subgrade conditions (e.g., material with a low value for Poisson's ratio) reduce the capacity to adequately transfer vertical loads in the horizontal direction radially about the point of load.

A geotextile placed beneath the affected weak subgrade enhances the subgrade stability by placing the fabric in tension and reduces the stress intensity at depths below the fabric. The component of the applied loads that are carried directly by the subgrade soil is reduced, and its ultimate load-bearing capacity is increased.

The designer is given the option of improving a soil's subgrade stability by placing a geotextile layer, which in most cases is more cost effective than removing or enhancing the subgrade through other methods. For applications to site access roadbeds, placement of a geotextile can decrease the thickness of the compacted aggregate base material (as shown on Figure 21). In situations where there is virtually no subgrade bearing capacity, a geotextile can provide the necessary support for applied loads. Sludge basins may exhibit minimal bearing capacity depending on the type of waste material and moisture content. A final cover system could not be placed over this type of basin unless the subgrade exhibited sufficient load-bearing capability. The use of a geotextile anchored and placed over the waste
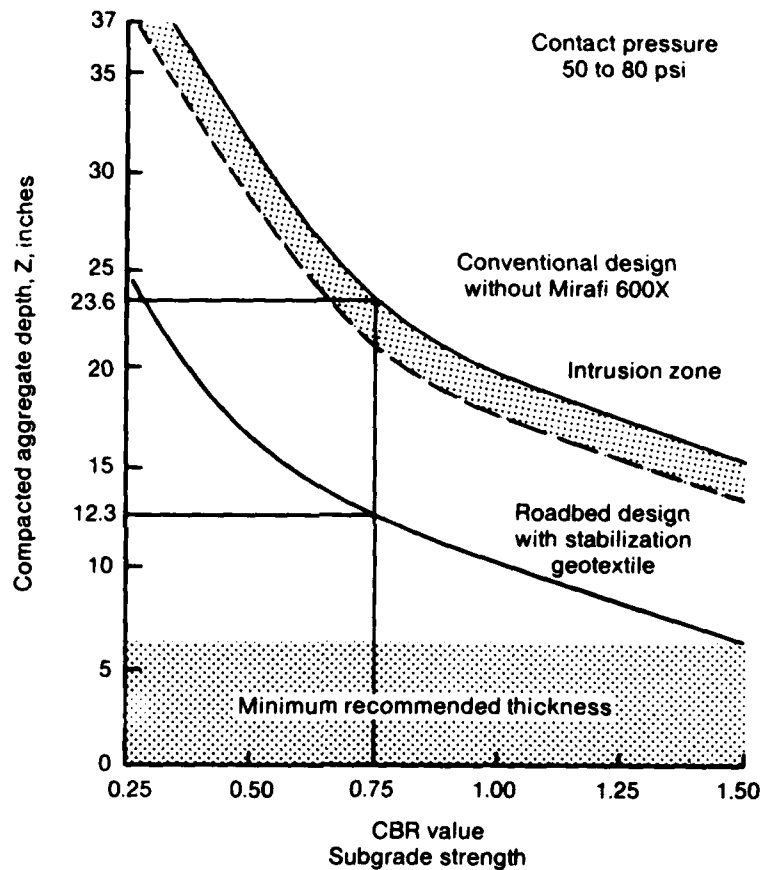
Adapted from Mirafi, "Ground Stabilization Fabrics...Design Guidelines"

Figure 21. Typical subgrade stabilization curves.

material may be considered a means of improving the load-bearing capacity over the basin area prior to placement of a cover system. Tnis concept is depicted on Figure 22. For the type of application shown on tnis figure, the geotextile material must be compatible with the waste material in the basin.

Geotextiles can be used to improve slope stability problems. Typically, slope stability is determined based on its resistance to failure, referred to as a factor of safety against failure (FS). For circular arc types of failure, a failure mode typical for earthen slopes, the following relation is evaluated (Koerner, 1980):

$$FS = \Sigma \frac{\text{resisting moments to failure}}{\text{driving movements for failure}} \tag{14}$$

$$= \frac{\tau\,LR}{Wx}$$

Where: τ = Snear strength of soil along the arc length L.

R = Radius distance from tne failure arc to tne hypothetical center of the slide.

W = Weight of soil mass in the potential slide.

X = Projected horizontal distance from the sliding mass center of gravity to the hypothetical slide center.

The shear strength is not a variable since it represents a characteristic of the soil. The otner terms in the equation are variables, and as such, can be altered by site work activities. In poor slope stability situations (soils exhibiting FS 1.0), geotextile fabrics can be placed to increase the factor ot safety against failure. Placement of the fabric across the potential failure plane shifts and increases the arc length of the failure surface. The fabric is placed in tension and carries a portion of the applied shear loading. The modified critical failure surface is changed, as new failure planes must extend beyond the fabric into less critical tailure surfaces. Figure 23 shows this shift in the failure surface and tne subsequent improvement in embankment stability. Appropriate geotextiles must exnibit high strengtn properties as well as good resistance to creep.
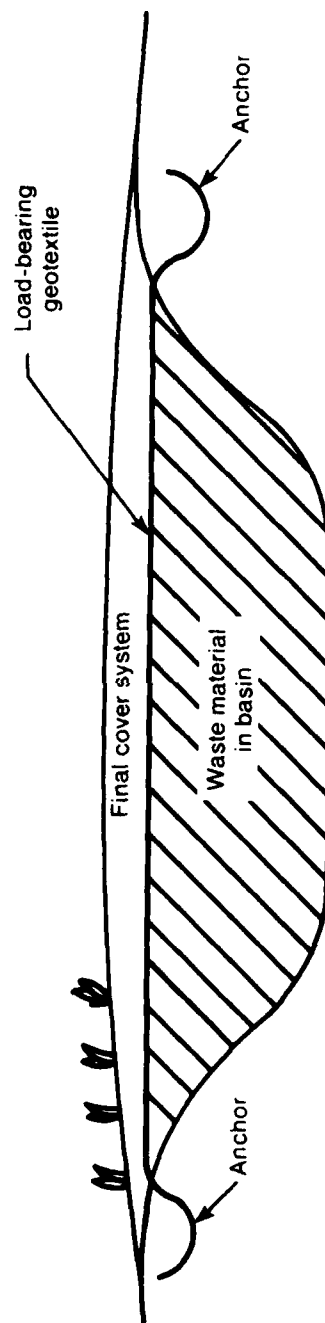
Figure 22. Load-bearing geotextile for improved subgrade.

Modified radius
failure surface

Original critical
failure surface

Fabric

Fabric

Fabric

Modified failure
surface of longer
arc length due
to fabric placement
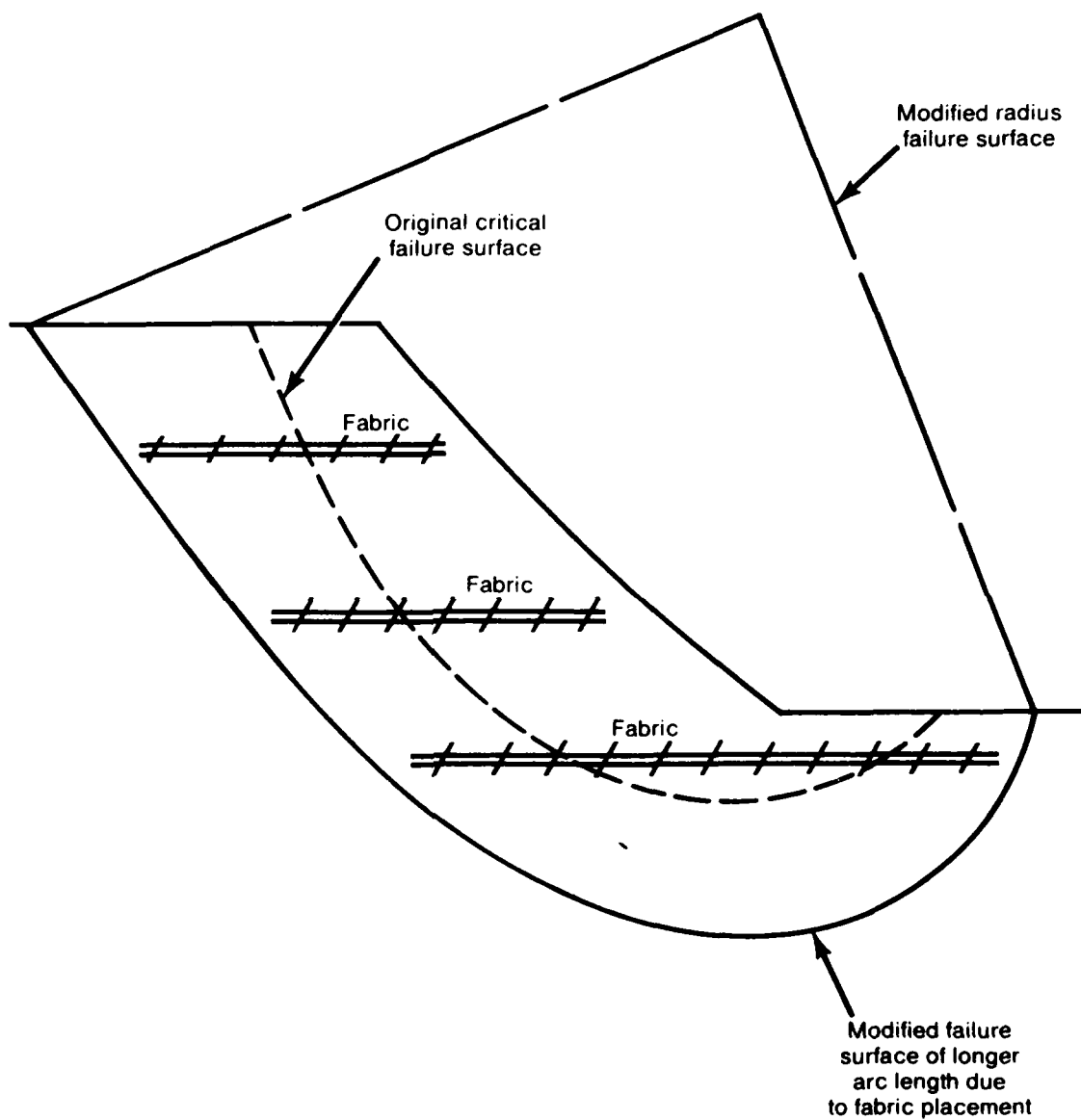
Adapted from Koerner, 1980

Figure 23. Application of geotextiles to slope stability improvements.

This type of use may be applicable to in-situ closure of basins in the follow cases:

(a) An existing dike or berm must be upgraded or improved in order to ensure long-term stability.
(b) A new dike or berm must be constructed but the shear strength of the soils is poor.
(c) An existing dike or berm must be increased in height and improved stability is desired.

As can be seen this type of application would be only applicable to "above-grade" basins/lagoons with earthern berms.

Subgrade drainage - Geotextiles can be applied to enhance subgrade drainage in the design of an underdrain system, as with the lining of a groundwater interceptor trench and as a base material in earthen dams and retaining walls. The use of a drainage fabric within a subsurface trench can significantly reduce the quantity of required backfill by eliminating the required use of filter material (as shown on Figure 24a).

Earthen dams typically incorporate a zoned or segmented construction approach, utilizing component layers that include riprap on the impoundment side, an impermeable clay corewall, and a chimmey drain and drainage gallery to transfer and direct subsurface flow. Geotextiles can be placed (as shown on Figure 24b) to enhance the function of each of these component layers. Geotechnical design factors to be considered when evaluating the use of drainage geotextiles in earthen dams include permeability (cross-plane and lateral in-place), clogging potential (fabric opening size), strength, and long-term durability.

In the design of retaining walls, consideration is given typically to reduction of hydrostatic pressure from the retained soils behind the wall. If relief of hydrostatic pressure through adequate drainage is achieved, the earth pressure acting on the wall is reduced. The removal of water from the backfill behind a retaining wall is generally accomplished through the placement of a 12 to 24-inch layer of high permeability soil directly behind the wall and through construction of drainage weep holes through the wall. As Figure 24c shows, drainage geotextiles can enhance the construction of such a filter layer and can reduce or potentially eliminate this layer. The selected geotextile fabric's in-plane permeability is the key design parameter to be considered.
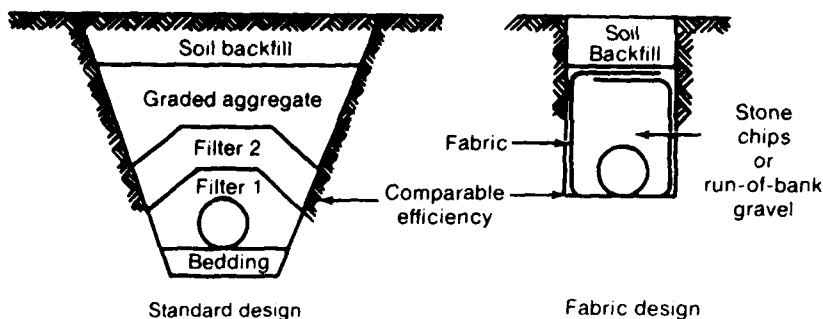
a Potential cross-sections of a
   geotextile-lined underdrain
   and interceptor trench
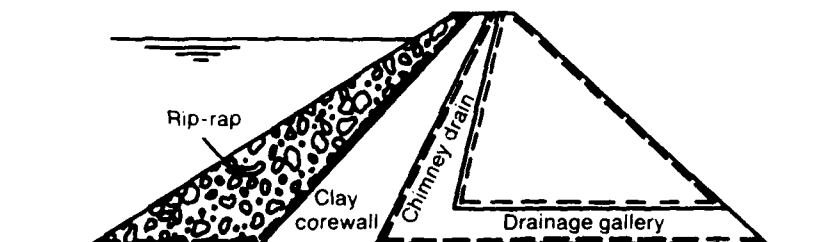
b Cross-section of zoned earth
   dam with geotextile
   applications (dashed lines
   show locations of fabric)
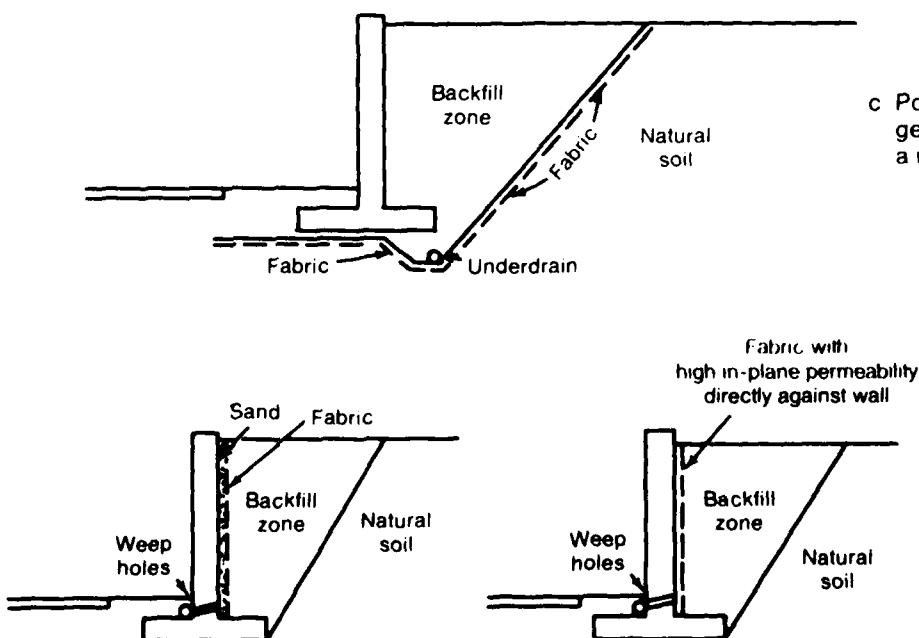
c Potential cross-sections of
   geotextiles places behind
   a retaining wall

Source: Adapted from Koerner, 1980

Figure 24.   Potential applications of drainage geotextile fabrics.

Possible applications to in-situ closure would be foi
instances when the closure plan incluaes the following:

(a) A groundwater interception trench.
(b) An underdrain (trench drain) system.
(c) A dam or retaining wall.

Soil erosion control - The prevention of soil erosion
primary concern in the application of almost every wast
tainment strategy. Vegetation represents a good soil e
preventative measure, provided critical slopes are not e
tered to prohibit vegetative growtn. Standard types of pav
including concrete, asphalt, riprap, and gabions, have be
plied successfully as well. Geotextile mesn sections an(
can be used to prohibit the loss of seed and vegetation
germination, ana because they are made of persistent synth
fabric mats can provide long-term erosion protection.

Construction geotextiles have been used to replace (
hance the function of granular filters beneatn erosion c(
structures. When faorics are placed in these situations, c(
eration must be given to the effects of harsh environmenta
ditions. The design of such erosion control geotextiles mu:
corporate the following fabric properties:

(a) High permeability.
(b) High tensile strength and elongation.
(c) Good resistance to tear and puncture.
(d) Long-term durability and resistance to ultraviol(
     gradation.

A significant problem presented through erosion is the
ot fine-grained soils from water and wind movement. Fabric
tencing can be incorporated to sieve out fine particles
pended in flowing water or to prevent the movement of so
wind forces.

Primary applications of erosion control geotextiles (
an in-situ closure project may include the following:

(a) Silt fences.
(b) Filter media in a rock dam.
(c) Matting to prevent washout of vegetation se(
     slopes.
(d) Filter media for sedimentation basin drains.

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3.5.2.2 Evaluation of geotextile properties; materials verification. Once the site conditions and desired application for the geotextile have been determined, a geotextile fabric must be selected based on its properties. The performance of a construction geotextile will only be as good as the weakest fabric property that it exhibits. Laboratory testing results are typically incorporated into an evaluation of geotextile properties. Table 7 describes the various laboratory tests utilized to assess the physical, mechanical, hydraulic, and performance properties of construction fabrics.

The geotextile fabric should be tested to verify that the material being supplied will meet the required specifications. This is the first step in the overall system verification process. If the material does not meet the stated specifications, failure of a component in the in-situ closure design may result.

Laboratory testing should address several or all (depending on application) of the tests shown in Table 7, but also compatibility testing between the waste and fabric material if appropriate.

3.6 Bio-barrier systems.

3.6.1 Process description. One concern regarding the long-term integrity of cap systems for use in an in-place containment strategy is the potential intrusion into cover soils by plant roots and burrowing animals. The burrowing animals are more of a problem in western states, (e.g., prairie dogs). The useful life of cap materials may be subject to a number of physical, chemical, and biological factors. Plant and animal breaching of the cap materials may lead to increased infiltration and a decline in the overall efficiency of the cap system for minimizing infiltration. Furthermore, burrowing animals in western states have been known to excavate large areas for habitation in soft clay soils and may carry waste materials to the surface of the site (Battelle, May 1982). Physical and chemical bio-barrier systems have been studied for application in waste containment, specifically in the long-term containment of uranium mill tailings.

TABLE 7.   LABORATORY TESTING OF GEOTEXTILES

Testing category	Fabric property	Standard test	Description/ relevance
I. Physical properties	Weight	ASTM D 1910	Mass per unit area.
	Thickness	ASTM D 1777	Distance between the upper and lower fabric surface under a specified pressure.
	Compressibility	ASTM D 1777	The fabric's thickness response to varying pressures; compressibility modulous is slope of curve.
II. Mechanical properties	Strip tensile strength	ASTM D 1682 and D751	Full width of fabric specimen gripped and pulled (loaded in tension) to failure.
	Grab tensile strength	ASTM D 1682 and D 751	Portion of the speciman width gripped and loaded in tension to failure; nonloaded portion of fabric provides transverse stiffness.
	Biaxial tensile strength	Modifed D 1682	"t" shaped specimen gripped and loaded in tension in perpendicular directions; useful in understanding fabric deformation properties under more accurate field conditions.

TABLE 7. (CONTINUED)

Testing category	Fabric property	Standard test	Description/relevance
	Elongation	ASTM D 1682	Percentage of specimen elongation measured under various tensile strength testing loads as the final elongation divided by the original length.
	Creep behavior	ASTM D 2990 (research stage)	The relationsip of elongation with respect to time, referenced as a percentage ratio of an elongation at a specified time to the initial fabric elongation.
	Abrasion resistance	ASTM D 1175	Measurement of the wearing away of fabric by abrasion from another surface; reported as percentage weight loss.
III. Hydraulic properties	Porosity	---	Scanning devices to identify fabric pore sizes, or Corps of Engineers equivalent opening size (EOS) as a modified sieve analysis for the fabric.
	Water permeability	---	Model water permeability of the fabric as done with soils; referenced as flow rate velocity.

TABLE 7. (CONTINUED)

Testing category	Fabric property	Standard test	Description/ relevance
	Planar water flow	---	Measurement of the fabric's ability to transmit water in a horizontal direction within the fabric plane.
	Soil retention or piping	---	Measurement of the fabric's ability to filter and retain soils and to act as a silt curtain at various flow velocities.
IV. Endurance properties	Chemical resistance	ASTM D 543	Provisions for measuring changes in weight, appearance, dimensions, and strength under standard chemical reagents.
	Weather/ultra- violet resistance	ASTM D 1435	Provisions for outdoor or other exposure simulation to various weather and ultraviolet light conditions.
	Temperature resistance	ASTM D 794 and D796	Measurement of the effects of extreme variations in exposure temperatures.
	Burial deterioration	---	Measurement of the effects of various soil conditions of organic content, pH, and microorganism content.

In some climatic and geographical areas, a plant root "barrier" may be needed to prevent roots from damaging the integrity of a cap system. Some laboratory and field experience has been gained in the use of stable polymeric carrier/delivery systems (PCD) to limit the potential intrusion of plant roots (Burton et al., 1978). A PCD system should be designed to perform the following functions (Battelle, September 1982):

(a) Provide a vehicle (polymer) that controls the release rate of the biocide into the soil near the barrier for an extended period of time.
(b) Select the biocide to be compatible with vegetation programs to stop root elongation at the barrier.
(c) Maintain an effective biocide concentration in a specified depth of soil and limit migration into the rest of the plant root zone to allow normal root growth above the barrier.

Burrowing animals have been identified in buried waste areas. Some of the burrowing animals of concern include, but are not limited to, blacktailed hares, badgers, marmots, prairie dogs, ground squirrels, pocket gophers, kangaroo rats, pocket mice, and chipmunks (Battelle, May 1982; Battelle, September 1982). Blacktailed hares were found burrowing in a radioactive waste disposal site and exposing radioactive salts (O'Farrell et al., 1975). At that radioactive site, an asphalt coating was placed as a bio-barrier over the burrowed area. Test results indicated that the asphalt pad was successful in isolating the wastes from the burrowing blacktailed hares (Uresk et al., 1975).

Development of bio-barriers has not reached the wide-scale implementation stage at present, but laboratory test results indicate favorable potential applications in waste management. Potential bio-barriers may include, but are not limited to, the following materials:

(a) Crushed rock or aggregate layers.
(b) Asphalt emulsion layers.
(c) Multilayer combinations of pea gravel, rock, clay mix, sand, or asphalt emulsion.
(d) Geotextile fabrics, reinforced fabrics, geotextile mesh.

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3.6.2 Process evaluation methodology.

3.6.2.1 Root system bio-barriers. Herbicides have been in use for many years to control the growth of plants, but single applications result in much higher concentrations than are necessary to control plant growth. Depending on site-specific conditions, the herbicide concentration in the soil decreases with time to a point where its remaining biocide action is less than the minimum effective level to control growth. Controlled release devices can effectively maintain a specified herbicide dose in the soil for prolonged periods of time. Polymers have been shown to be excellent delivery systems because they can function as a herbicide reservoir and as a herbicide release-regulating mechanism, and can protect the herbicide from degradation (Battelle, September 1982). Figure 25 shows the time-dependent relationship of herbicide concentrations in the soil for single applications and controlled release doses.

From the results of a study conducted by Battelle, the use of time-controlled release herbicides from PCD systems would be effective in limiting deep root penetration. Laboratory tests indicated successful applications of the herbicide trifluralin in sheets of polymers that were placed in vegetated plant columns (Battelle, September 1982). The herbicide-treated polymer sheets inhibited the penetration of plant roots for the desired length of time (see Figure 26).

Field tests were developed to assess the actual applications of PCD systems to waste management. Those results indicated that a PCD system in pellet form would be an effective and desirable method to control the release of a herbicide in the field. Cylindrically-shaped pellets could be placed to supply a time-released dose of trifluralin herbicide for an active period of up to 100 years. Additional work remains to assess the long-term durability of time-released PCD capsules, the effects of temperature on release rates, and any supplemented methods that could be developed.

3.6.2.2 Animal intrusion bio-barriers. A second major function of a bio-barrier is to prohibit the intrusion of the multilayer cap system by animals. In field work at radioactive tailings disposal sites, burrowing animals were studied. Prairie dogs and ground squirrels were two animal species of predominant concern. Ground squirrels are medium-sized burrowers, while heavier prairie dogs are capable of more destructive burrowing. At two test facilities, animal bio-barriers were studied for their effectiveness.
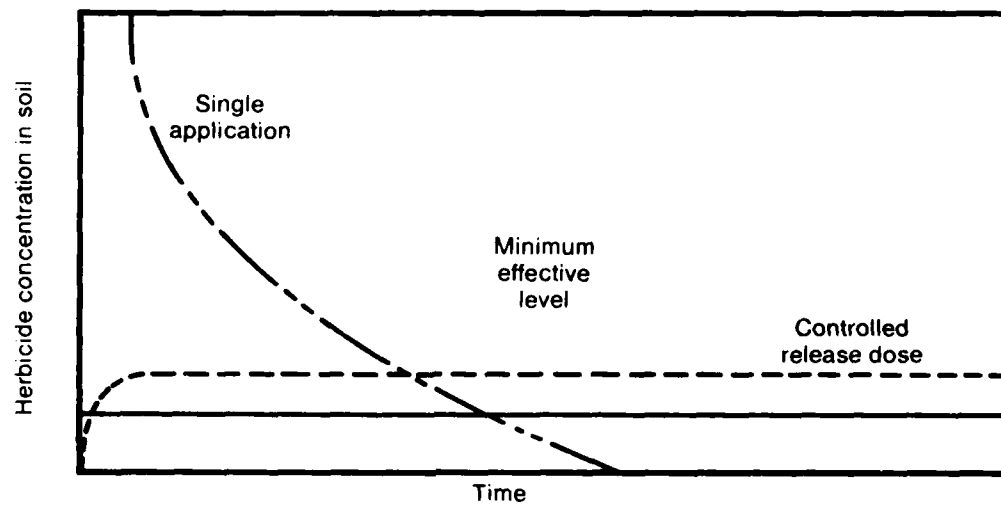
Figure 25.   Time-dependent comparison of herbicide levels in soils.
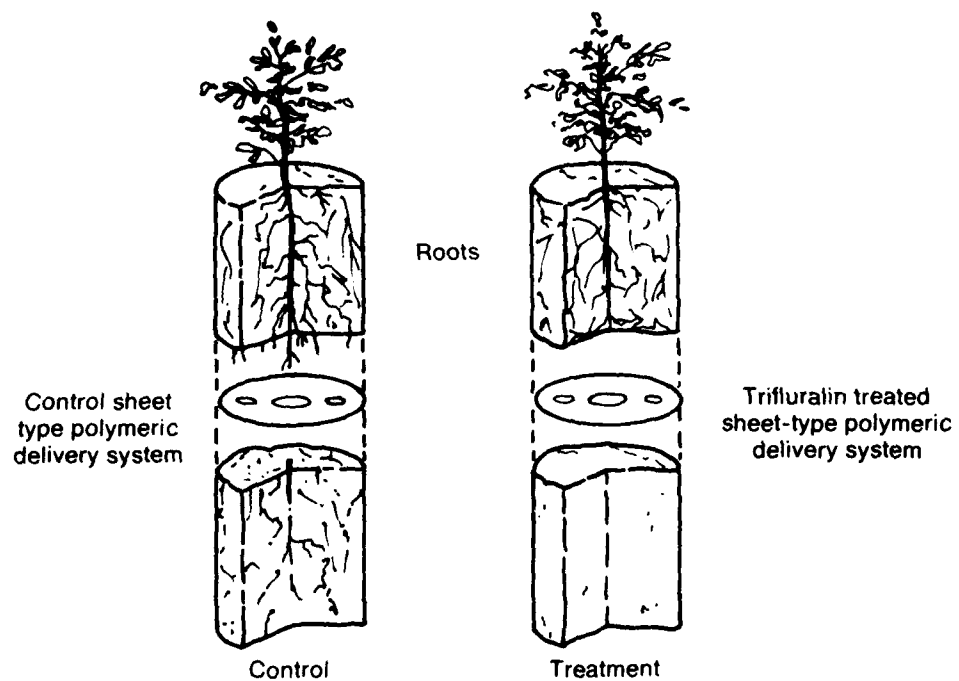
Figure 26. Laboratory assessment of the effects of trifluralin-treated polymers on root penetration.

Three types of bio-barriers were placed in test pens (see Figure 27) in which ground squirrels and prairie dogs were introduced. The results, although not totally successful or conclusive, showed some promise. Ground squirrels did not penetrate any rock barrier, asphalt emulsion, or multilayer earth seal. Prairie dogs, however, were able to penetrate a rock barrier constructed from 1-1 1/2 inch crushed stones. Additional research and field tests should be conducted with barriers made from larger angular rocks (to prevent intrusion of larger burrowing animals), geotextiles and reinforced fabrics, and mesh layers.

I Multilayer earth seal — 18 inches soil / Pea gravel / 6 inches rock / 6 inches clay mix / 6 inches sand / Soil

II Rock barrier — 18 inches soil / Pea gravel / 12 inches rcok / 3 inches asphalt emulsion / Soil

III Asphalt emulsion seal — 18 inches soil / Pea gravel / 3 inches asphalt emulsion / Soil
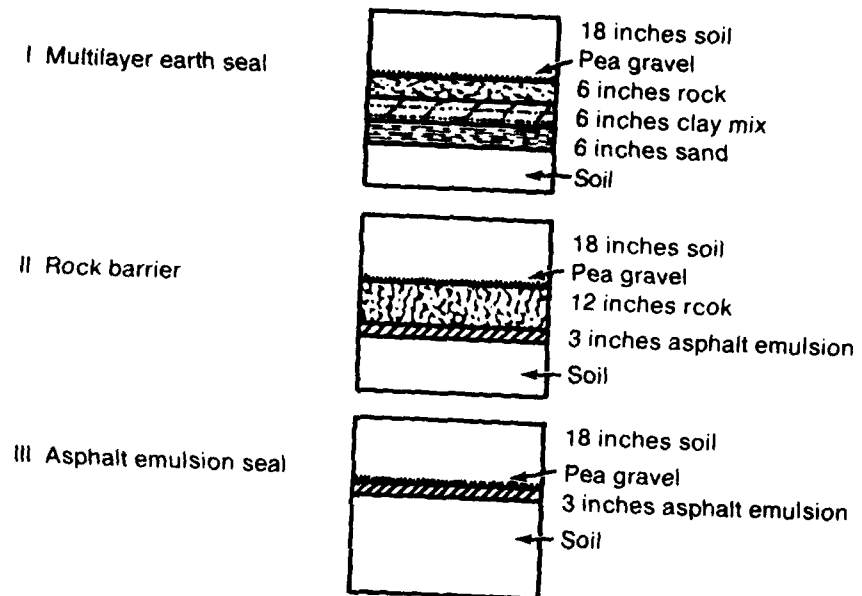
Figure 27.   Potential animal intrusion bio-barriers

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4. NONSOIL CAPS AND LINERS

4.1 <u>Introduction</u>. Lagoon containment may be achieved through the use of impermeable caps and liners. As previously discussed in Section 3, the primary objective of a surface cap is to contain waste materials and impede the flux of water from precipitation into a waste disposal area and thereby limit the potential for leachate generation. Other objectives of surface capping are associated with providing a physical barrier to achieve the following:

(a) Control possible human contact with waste materials.
(b) Control rodent burrowing or animal contact with the waste.
(c) Control water erosion that may result in transport of waste materials.
(d) Control wind erosion and dust generation.
(e) Preserve containment.

These objectives are discussed in detail in Section 3.

The function of impermeable lagoon liners is to contain wastes and to stop the flow of pollutants into the subsoil and the groundwater. Liners may be used in lagoon closure in cases where wastes are excavated from the lagoon and possibly treated. The lagoon can then be lined, followed by re-emplacement of the lagoon contents, and possible capping of the lagoon for final closure.

Nonsoil cap and liner materials commonly used for waste containment include the following:

(a) Asphalts.
(b) Concrete.
(c) Synthetic polymer membranes.

Brief descriptions of the use of these materials for waste containment are contained in the subsections that follow.

4.2 Nonsoil cap and liner materials.

4.2.1 Asphalts.

4.2.1.1 Asphalt emulsion (spray asphalt). Histc
asphalt has had a productive life as a waterproofing ag
ing back more than 5,000 years. Early uses were simple
cluded caulking and cementing agents for baths and sim
draulic structures. Past and present applications take a
of the thermoplastic properties of asphalt. Liners or
be formed in the field by spraying a prepared surface w
uid asphalt, which then solidifies to form a continuous
tight membrane.

Proper spray technique is important, but technical
are always involved when spraying any material directl
prepared surface such as soil. Since asphalt is spra·
unidirectional fashion, it is very difficult to ensure
cover due to small protuberances that receive only part
er. Sprayed-on liners are seam free, but preparing th
hole" free in the field sometimes poses serious difficul

Recent use of asphalt materials for waste contain
snown that asphalt is resistant to weak acids, bases, i
salts, and corrosive gases. Asphalts, however, are gener
resistant to organic solvents (Haxo, 1982).

The design life of asphalt containment systems is
mately 50 years (EPA, 1982).

4.2.1.2 Asphalt concrete (hydraulic asphalt). Hi·
ly, an asphalt-based material (asphalt concrete) has b
as a seepage barrier for many thousands of years. As a c
a pure membrane it helped the early civilizations to wa
their canals and aqueducts, and later their baths an
conduits. Some of these facilities are still in use, a
to the longevity of asphalt. Despite these fine credentj
phalt concrete must be used properly in today's hydrauli
tures if lasting results are to be obtained.

Some confusion has developed from data generated wi
laboratory where it is possible to produce asphalt concr
ples with zero porosity. The problem arises from the i
of contractors to duplicate the laboratory results ov
areas in the field. Good performance from an asphalt
cover demands careful attention to both mix design and i
tion details. The control of mix temperatures at the
spreading, the time lag between this operation and con
and the compacting effectiveness itself are three impor
sometimes difficult parameters to control.

Sun aging, creep tendencies, and normal subgrade movements may also combine to reduce the effectiveness of asphalt covers and liners unless these issues are adequately addressed in the design. Additionally, if unprotected, asphalt concrete is subject to damage due to icing conditions, which can cause a spalling effect. Asphalt concrete cannot be used on vertical slope work; generally its use is restricted to slopes of no greater than 2:1 (Kays, 1977).

Asphalt concrete cover and liner systems may be subject to penetration by weeds. The black asphalt blanket absorbs heat readily and serves as an incubator for the weed seeds that lie below it. The problem is more or less eliminated if the structure is covered; otherwise, a soil sterilant is often used, particularly if the facility is built in a location where weed growth is suspect.

Asphalt concrete is compatible with most wastes; however, the capital and placement costs will usually exceed that of low permeability soil liners/caps if suitable soils are available locally.

4.2.2 Concrete. Concrete is technically not an impervious material in the strictest sense of the word. In the laboratory it is possible to make a test sample that possesses rather good resistance to the passage of water, but in the field this is not an easily-attainable goal. Construction joints present leakage problems, and field-applied concrete membranes have widely-varying degrees of permeability. Good-quality concrete also has the tendency, in time, to degrade with respect to its waterproof qualities (Kays, 1977).

The importance of subgrade conditions cannot be overemphasized in connection with unreinforced concrete covers or liners. Although many of the flexible cover systems can tolerate some variance with respect to substrata stability, plain concrete cannot. Concrete covers and liners without reinforcement are particularly vulnerable to the actions of frost, swelling, and shrinkage within the soils on which they rest. Undesirable surface soil conditions may be remedied by removing the portion of the subgrade in question and replacing it with a material of the desired properties. Nonexpansive materials are used, placed in layers not exceeding 6 inches, and compacted to at least 90 percent of standard maximum density (Kays, 1977).

Concrete of good quality is resistant to many naturally-occurring chemicals. When properly proportioned, placed, and cured it is relatively impervious to most water, soil, and atmospheric conditions. Extremely high material and construction costs, however, often limit the use of concrete as a waste containment material.

There are some chemical environments under which the useful life of the best concrete will be shortened, and knowledge of these conditions permits measures to be taken to counteract or prevent deterioration. Most corrosive chemicals must be in solution and above some minimum concentration to produce a significant attack on concrete. Concrete is rarely, if ever, directly attacked by soil or dry chemicals. Concrete that is subjected to aggressive solutions under pressure is most vulnerable because the pressures tend to force the aggressive solution into the concrete. When free evaporation can also take place from an exposed face, dissolved salts may accumulate at that face, thus increasing their concentration and possibly resulting in mechanical damage from spalling in addition to chemical attack.

4.2.3 Synthetic polymer membranes. Flexible synthetic membranes are assuming increased importance as containment materials because of their very low permeability. These covers are products of the plastics and rubber industries. The polymeric materials used in the manufacture of these covers and liners include vulcanizable and nonvulcanizable thermoplastics, plastics, and rubbers. They are all synthetic materials, varying from highly polar polymers, such as polyvinyl chloride (PVC), to non-polar polymers, such as EPDM and butyl. They range from amorphous polymers, such as the rubbers, to crystalline polymers, such as polyethylene. Generally, polymeric materials are compounded with fillers, antidegradants, plasticizers, and curatives if vulcanization is needed. Compounds based on the same polymer can vary considerably in composition from manufacturer to manufacturer, depending on the grade and the price of the material.

The membrane sheeting is usually made in a continuous process. Many liners are single ply 30 mil. Plying is used predominantly when liners are reinforced. Most of the sheets are 10 to 12 feet wide when made (width is a function of the fabricating equipment). Fabric reinforcement, usually a nylon or polyester scrim, can be sandwiched between these plies to give added strength to the cover. Sheets are typically 4 to 5 feet wide and 200 feet long. Several of these sheets can be seamed by a fabricator in a factory to form a panel.

In general, synthetic covers and liners are susceptible to the same types of long-term failure mechanisms as asphalts and concrete. In addition, synthetic membranes are prone to punctures due to root penetration and damage during placement. Severe puncture damage can result in the escape of pollutants and surface-water infiltration. Synthetic membranes are also prone to microbial attack, which, in the context of a permanent closure plan, becomes a significant consideration. The design life of synthetic membranes is expected to be about 20 years (EPA, 1982).

A list of membrane materials, plus the relative advantages and disadvantages of various polymer membranes currently used for waste containment, are presented in Table 8.

A few representative types of synthetic polymer membranes are described in greater detail in the subsections that follow.

4.2.3.1 Chlorosulfonated polyethylene (CSPE). Chlorosulfonated polyethylene is a family of polymers prepared by reacting polyethylene in solution with chlorine and with sulfur dioxide. Presently available polymers contain from 25 to 43 percent chlorine and from 1.0 to 1.4 percent sulfur (Matrecon, 1980). These polymers can be used in both thermoplastic (uncross-linked) and in vulcanized (cross-linked) compositions. Uncured CSPE is more thermoplastic than other commonly used elastomers. It is generally tougher at room temperature, but softens more rapidly as temperatures are increased.

Chlorosulfonated polyethylene is characterized by ozone resistance, ultraviolet stability, heat resistance, good weatherability, and resistance to deterioration by corrosive chemicals. It has good resistance to the growth of mold, mildew, fungus, and bacteria. Membranes of this material are available in both vulcanized and thermoplastic forms, but primarily in the latter. Usually these materials are reinforced with a polyester or nylon scrim, and generally contain at least 45 percent CSPE polymer (Matrecon, 1980). The fabric reinforcement gives needed tear strength to the sheeting for use on slopes, and reduces the distortion resulting from shrinkage when placed on the base, and when exposed to the heat of the sun.

Chlorosulfonated polyethylene can be seamed by heat sealing, dielectric heat sealing, solvent welding, or by using "bodied" solvent adhesive. Membranes of this polymer do not crack or fail

TABLE 8. DESCRIPTION OF POLYMER MEMBRANES USED FOR WASTE CONTAINMENT

Type	Composition	Advantages	Disadvantages
Butyl rubber	Co-polymer of isobutylene (97 percent) and small amounts of isoprene. Usually vulcanized.	1. High resistance to mineral acids. 2. Good tensile strength. 3. Ozone and weathering resistance. 4. High tolerance to temperature extremes.	1. Highly swollen by hydrocarbons. 2. Difficult to seam and repair, special vulcanizing adhesive required. 3. Slightly affected by oxygenated solvents.
Chlorinated polyethylene (CPE)	25 to 45 percent chlorine with 0 - 25 percent crystallinity. Usually unvulcanized.	1. Resistant to many acids and alkalies. 2. Good resistance to biological degradation. 3. Ozone resistant. 4. Often alloyed with PVC, PE, and synthetic rubber.	1. Swells in high concentrations of aromatic hydrocarbons and oils.
Chlorosulfonated polyethylene (Hypalon)	25 to 43 percent chlorine with 0 - 1.4 percent sulfur. Usually unvulcanized.	1. Resistant to acids and alkalies. 2. Ozone resistant. 3. Resists molds and mildews.	1. Shrinks and hardens from exposure to ultraviolet light. 2. Will soften at elevated temperatures. 3. Low tensile strength. 4. Poor resistance to oils. 5. Swells in the presence of aromatics.
Ethylene propylene rubber (EPDM)	Terpolymer of ethylene, propylene, and a minor amount of nonconjugated diene hydrocarbon. Usually vulcanized.	1. Excellent ozone resistance. 2. Tolerates extremes in temperature. 3. Resistant to dilute solutions of acids, alkalies, silicates, phosphates, and brine. 4. Good abrasion resistance.	1. Not recommended for petroleum, aromatic, or halogenated solvents. 2. Special vulcanizing adhesives required for seaming and repair.

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TABLE 8. (CONTINUED)

Type	Composition	Advantages	Disadvantages
Neoprene	Generic name of synthetic rubbers based on chloroprene. Vulcanized.	1. Resistant to oils and acids. 2. Mechanical properties similar to natural rubber with resistance to puncture and abrasion.	1. Vulcanizing cements required for seaming and repair.
Polyethylene, high density (HDPE)	Based on ethylene with 2 to 3 percent carbon black; density varies. Unvulcanized.	1. Superior resistance to oils and solvents.	1. Special seaming tools required. 2. Clear polyethylene readily degrades on outdoor exposure. 3. Very stiff compared to other liner materials.
Polyvinyl chloride (PVC)	Produced from vinyl chloride; 25 to 35 percent plasticizers, 1 to 5 percent chemical stabilizer, and microbiocide added.	1. Good resistance to many organic chemicals. 2. Good tensile strength and elongation properties.	1. Affected by ultraviolet exposure. 2. Heat of the sun can volatilize plasticizers. 3. Susceptible to attack from hydrocarbons, oils, and solvents.
Oil resistant polyvinyl chloride (PVC-OR)	Similar to PVC with additional oil-resistant compounding ingredients.	1. Good resistance to many organic chemicals. 2. Good tensile strength and elongation properties. 3. Good oil resistance.	1. Affected by ultraviolet exposure. 2. Heat of the sun can volatilize plasticizers.
Ethylene interpolymer alloy	Alloy of elasticized polyolefin.	1. Resistant to many chemicals. 2. Good oil resistance. 3. Good temperature service. 4. Good weathering.	1. Not recommended for organics, especially aromatic. 2. Low temperature limitations.
Polypropylene	Based on propylene with carbon black added. Unvulcanized.	1. Resistant to many chemicals. 2. Superior high temperature service. 3. Good low temperature service. 4. Good tensile strength.	1. Susceptible to ultraviolet and ozone attack. 2. Difficult to seam in the field. 3. Not recommended for oxidizing solvents.

Sources: 1. Lining of Waste Impoundment and Disposal Facilities, SW-870, U.S. EPA, Office of Water and Waste Management.

2. Engineering and Development Support of General Decon Technology for the DARCOM Installation Program, Task 7. Literature search and evaluation of compatibility testing of waste containment barrier materials.

3. Gibbons et al., 1983.

trom temperature extremes or weathering. Disadvantages of CSPE membranes include low tensile strength and a tendency to shrink when exposed to sunlight. Some CSPE's tend to harden with age due to cross-linking by moisture, ultraviolet radiation, and heat.

4.2.3.2 Polyvinyl chloride (PVC). Polyvinyl chloride (PVC) membranes are probably the most widely used of all polymeric membranes for waste impoundments. Polyvinyl chloride is produced by many of several polymerization processes from vinyl chloride monomer (VCM). It is a versatile thermoplastic polymer that is compounded with plasticizers and other modifiers to produce a wide range of physical properties.

Polyvinyl chloride membranes are produced in roll form in various widths and thicknesses. Polyvinyl chloride compounds contain 25 to 35 percent of one or more plasticizers to make the sheeting flexible and rubber-like (Matrecon, 1980). The sheeting also contains 1 to 5 percent of a chemical stabilizer, and various amounts of other additives. The PVC compound should not contain any water-soluble ingredients.

There is a wide choice of plasticizers that can be used in PVC sheeting, depending on the application and service conditions under which the PVC compound will be used. Plasticizer loss during service is a source of PVC degradation. There are three basic mechanisms for plasticizer loss: volatilization, extraction, and microbiological attack. Polyvinyl chloride polymer generally holds up well in burial tests, however, compounds of PVC films have deteriorated, presumably due to microbial attack (Wendt, 1980). The use of the proper plasticizers and an effective biocide can virtually eliminate microbiological attack and minimize volatility and extraction (Scullin, 1965). The PVC polymer itself is not affected by these conditions; however, it is affected by ultraviolet exposure.

The principal reason for loss of plasticizer is by volatilization in the heat of the sun rather than solution in the waste fluid. Carbon black prevents ultraviolet attack, but causes the absorption of solar energy, thus raising the temperature to a high enough level to cause vaporization of the plasticizer. The soil or other suitable cover material used to bury the cover protects it from ultraviolet exposure and reduces the rate of plasticizer loss. Polyvinyl chloride sheeting is not recommended when it will be exposed to weathering and ultraviolet light conditions during its service life.

Plasticized PVC sheeting has good tensile, elongation, and puncture- and abrasion-resistance properties. It is readily seamed by solvent welding, adhesives, and heat and dielectric methods. Finally, PVC shows good chemical resistance to many inorganic chemicals.

4.2.3.3 Neoprene. Neoprene is the generic name of synthetic rubbers based on chloroprene. These rubbers are vulcanizable, usually with metal oxides, but also with sulfur. They closely parallel natural rubber in mechanical properties, e.g., flexibility and strength. Neoprene, however, is superior to natural rubber in its resistance to oils, weathering, ozone, and ultraviolet radiation; it is also resistant to punctures, abrasion, and mechanical damage.

Neoprene membranes have been used primarily for the containment of wastewater and other liquids containing traces of hydrocarbons. They also give satisfactory service with certain combinations of oils and acids for which other materials do not provide long-term service (Matrecon, 1980).

Vulcanizing cements and adhesives must be used for seaming neoprene.

4.2.3.4 Chlorinated polyethylene (CPE). Chlorinated polyethylene (CPE) is produced by a chemical reaction between chlorine and high-density polyethylene. Presently available polymers contain 25 to 45 percent chlorine and 0 to 25 percent crystallinity (Matrecon, 1980). Chlorinated polyethylene is compounded and used in thermoplastic and cross-linked compositions.

Since CPE is a completely saturated polymer (no double bonds), it is not susceptible to ozone attack and weathers well. The polymer also has good tensile and elongation strength. Chlorinated polyethylene is characterized by resistance to deterioration by many corrosive and toxic chemicals. Because they contain little or no plasticizer, CPE covers have good resistance to the growth of mold, mildew, fungus, and bacteria. Membranes made of CPE can also be formulated to withstand intermittent contact with aliphatic hydrocarbons and oils. CPE will swell in the presence of high concentrations of aromatic hydrocarbons and oils, but regains some of its original properties when removed from that environment.

CPE can be compounded with other polymers, making it a feasible base material for a broad spectrum of membranes. CPE can be alloyed with PVC, polyethylene (PE), and numerous synthetic rubbers. Usually, at least half the polymer content of CPE membrane is CPE resin. This compound is widely used to improve the stress crack resistance and softness of ethylene polymers, and to improve the cold crack resistance of flexible polyvinyl chloride. Chlorinated polyethylene membranes are available in varied thicknesses in unreinforced or fabric-reinforced versions. Membranes of CPE are generally unvulcanized and thus can be seamed by bodied-solvent adhesives, solvent welding, or dielectric heat sealing.

4.2.3.5 Ethylene propylene (EPDM). EPDM is a thermoplastic grade of ethylene propylene rubber. The liners are constructed of multiple layers of EPDM sheeting laminated to one or two layers of nylon or polyester reinforcing fabric.

EPDM is immune to the effects of ozone, and offers excellent resistance to temperature extremes, oxidation, ultraviolet light, and a wide range of acids, bases, salts, and corrosive chemicals. EPDM can be fabricated in large factory-seamed panels to minimize onsite seaming; it is also free of pinholes, and will not delaminate.

Another feature of EPDM is that it can be heat-seamed at the job site with simple heat tools by semi-skilled personnel. The heat seam sets within seconds to a strength exceeding that of the parent material. Disadvantages of EPDM liners include low resistance to some hydrocarbons and a relatively short expected lifetime.

4.3 Methodology for evaluation of cover and liner containment systems. A critical part of the sequence of designing, constructing, and maintaining an effective containment system for lagoon wastes is the systematic evaluation of engineering criteria. First, the individual performance criteria are assessed and standardized. Each cover and liner type is then evaluated based on each of the performance criteria, and the most suitable containment system is selected for further development. Performance criteria for covers and liners are presented in Tables 9 and 10, respectively.

TABLE 9. COVER MATERIAL PERFORMANCE CRITERIA

1. Historical applications as a cover material.

2. Trafficability.

3. Ability to impede water percolation.

4. Freeze/thaw stability.

5. Seismic stability.

6. Crack resistance.

7. Resistance to ultraviolet exposure from sunlight if it is not covered.

8. Side-slope stability.

9. Ability to discourage rodent burrowing.

10. Ease of construction and constructability; seaming and seam integrity inspection techniques.

11. Ability to impede plant root penetration.

12. Cost of placement.

13. Resistance to biological degradation.

14. Compatibility with lagoon wastes and any gases or volatiles generated by the wastes.

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TABLE 10. LINER MATERIAL PERFORMANCE CRITERIA

1. Provides containment for leachate.

2. Historical application as a liner material.

3. Seismic stability.

4. Crack resistance.

5. Resistance to root penetration.

6. Potential for damage to liner during placement.

7. Ease of construction and constructability; seaming and
    seam integrity inspection techniques.

8. Resistance to biological degradation.

9. Cost of placement.

10. Compatibility of lagoon wastes.

4.4 **Applicability to lagoon closure.** In order to provide an example of an evaluation methodology, a number of representative types of nonsoil containment materials were evaluated with respect to applicability to in-situ lagoon closure. It should be recognized that this evaluation does not take into consideration all possible types of containment materials and thus is not meant to be a complete investigation, but rather, the evaluation is intended to be a preliminary assessment of containment alternatives, and may serve as a guideline for future assessments.

Containment materials were evaluated based on the performance criteria discussed in the previous subsection. The results of the performance evaluation are presented in Table 11 for covers and Table 12 for liners. If a containment material was given a positive performance rating, a plus sign appears in that criteria column. A positive rating denotes that a particular material exhibits a relative advantage with respect to that performance criterion. If a negative performance rating was given, a minus sign appears in the criteria column. A minus denotes a negative disadvantage for that material with respect to that performance criterion. Individual performance criteria are addressed in the subsections that follow. The performance criteria that are not discussed are self explanatory.

TABLE 11. CAP MATERIAL GENERAL PERFORMANCE ASSESSMENT

Cover Material	Historical applications as a cover material	Trafficability	Impede water percolation	Resistance to weathering	Freeze/thaw stability	Seismic stability	Crack resistance	Side-slope stability	Discourages rodent burrowing	Ease of construction	Cost of placement	Biological deterioration	Root penetration	Compatibility with explosives	Compatibility with organic solvents
Spray asphalt emulsion	+	-	+	-	-	-	-	-	+	+	+	-	-	II	-
Hydraulic asphalt	-	+	+	+	+	+	+	+	+	-	-	+	+	II	-
Synthetic -- Hypalon	+	-	+	+	+	-	-	-	-	-	-	-	+	+	+
Synthetic -- PVC	+	-	+	-	+	-	-	-	-	-	-	-	+	+	+
Synthetic -- neoprene	-	-	+	+	+	-	-	-	-	-	-	-	+	+	+
Synthetic -- CPE	+	+	+	+	+	+	+	+	+	-	-	+	+	+	-
Reinforced concrete	+	+	+	+	+	-	-	+	+	+	+	+	II	II	II

Key: + = Positive performance rating.
      - = Negative performance rating.
     II = Insufficient information available to make a determination.

TABLE 14. LINER MATERIAL GENERAL PERFORMANCE ASSESSMENT

Liner material	Provides reliable containment for leachate	Historical application as liner material	Seismic stability	Crack resistance	Root penetration	Potential for damage to liner during placement	Ease of construction	Biochemical deterioration	Cost of placement	Compatibility with explosives	Compatibility with organic solvents
Spray asphalt emulsion	-	+	-	-	-	+	+	-	+	II	-
Hydraulic asphalt	+	+	-	+	+	+	+	+	-	II	-
Synthetic -- Hypalon	+	+	-	+	-	-	+	-	-	+	-
Synthetic -- PVC	+	+	-	+	-	-	+	-	-	+	-
Synthetic -- neoprene	+	+	-	+	-	-	+	-	-	+	-
Synthetic -- CPE	+	+	-	+	-	-	+	-	-	+	-
Reinforced concrete	+	+	+	+	+	+	-	+	-	II	II

Key: + = Positive performance rating.
     - = Negative performance rating.
     II = Insufficient information available to make a determination.

r... t...se evaluation tables it can be seen that certain
....ve disadvantages with respect to application. Th
p...... ilawoacks must be considered as part of the final
.... .xample, if a material exhibits poor side-slope s
.... the final side slopes must be reduced to a m
.... .reclude possible failure. If a material
.... .pect to weathering or freeze/thaw, then a p
.... .r may be needed for placement over the ma
.... criteria cannot be fully addressed as part of
.... design. These criteria may include waste/li
.... and construction costs.

4.4.1 Containment material performance criteria.

4.4.1.1 Ability to withstand construction and maintena
vehicle tratfic. This criterion evaluates the ease by wh
construction and maintenance vehicles can maneuver on the ma
rial. In this evaluation, concrete and asphaltic cover materi
were given positive performance ratings due to their wide use
highway construction applications. Synthetic membranes w
given negative performance evaluations because vehicle traf
may result in damage to the membrane unless it can be protect
Thick layers of soil and geotextiles have been used as prot
tive measures for synthetic membranes.

4.4.1.2 Ability to impede water percolation. The abil
to impede water percolation is a major criterion in evaluat
containment materials. Cap and liner materials were evaluated
their respective permeabilities. Generally, materials with p
meabilities less than 10^{-5} cm/sec were given favorable p
formance ratings.

4.4.1.3 Resistance to weathering. Most of these cap
liner materials will be subject to damage in the long term
t.ey are not protected, however, several of the materials w
undergo deterioration in a shorter time frame. If the protect
cover is damaged this deterioration could occur before repa
could be made. Spray asphalt used as a cap is subject to dam
trom surface runoff, freeze/thaw, traffic, and animal atta
PVC and nypalon used as a cap or liner are subject to degra
tion through ultraviolet exposure.

4.4.1.4 Freeze/thaw stability. In cold regions of
country, special attention may need to be directed to the
tects of freezing. Freeze/thaw characteristics of all cov
liner, and subgrade materials must be determined and cross-r
erenced with depth of frost penetration in the region of c
cern. Where more detail on frost depth is needed, or in mo
tainous terrain where the depth of freezing can vary over sh

distances, frost penetration data must be obtained from local agricultural agencies. In general, subgrades consisting of inorganic silts and very fine sands with slight plasticity demonstrate major heave characteristics, and, therefore, are greatly susceptible to freeze/thaw fractures. On the other hand, sandier soils are susceptible to fast freeze conditions and therefore, deeper frost penetration. It should be noted that concrete is also susceptible to freeze/thaw fracturing, however, this problem can be remedied by proper mix design. Most freezing problems relating to cap systems can be remedied by a sufficiently thick topsoil cover. In general, freeze/thaw is not a critical issue for liner materials because the liner is buried beneath a thick layer of waste material. The edges and anchor perimeter of the layer may be near the ground surface and freeze/thaw may be an issue.

4.4.1.5 Seismic stability. For waste lagoons subject to earthquakes but not located on an active fault, damage to such a lagoon from ground shaking may include the differential settlement of the foundation soils and wastes leading to strains in the liners and covers. If these strains are localized or large in magnitude, failure of the liner or cap may occur. Detecting the location and repairing the damaged liner section would be very difficult. Repairing a damaged cap would not be as difficult.

Ground motions also cause stress changes in the lagoon and natural slopes. Landslides in the natural slopes surrounding the lagoon may block access roads and diversion structures. Landslides into the lagoon may damage the cap and possibly displace the encapsulated waste. The potential magnitude of waste material released due to failure of any portion of the waste lagoon as a result of earthquakes will be influenced by the following:

(a) The magnitude of the earthquake.
(b) The distance from the waste impoundment to the active fault.
(c) The soil conditions under the site.
(d) The nature of the waste.
(e) The closure plan employed.

Containment materials were evaluated based on their ability to withstand minor seismic disturbances.

Reinforced concrete was given a positive performance rating since concrete can and is often designed for earthquake stability. Many construction and design codes exist for protection of concrete structures from earthquakes.

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Synthetic polymer materials and asphalts were given poor performance ratings because of their generally low tensile and shear strengths.

4.4.1.6 Crack resistance. This evaluation was based on each containment material's ability to resist cracking due to differential settlement of the subgrade. Other phenomena, such as water erosion and weathering, could also cause the containment material to crack, however, these performance criteria were evaluated previously. Cracking due to differential settlement of the subgrade is a function of both the sheer and tensile strength of the containment material.

Synthetic membranes as a group were given lower performance ratings due to their inability to relieve the stress caused by differential settlement of the subbase. This continued stress in synthetic membranes after a differential displacement of the subbase is believed to be the ultimate cause of failure in such membranes. Proper compaction and preparation of the subbase is crucial for the placement of a synthetic membrane. A membrane can withstand some minor settlement, however, excessive differential settlement will cause failure.

Construction-grade paving materials such as hydraulic asphalt and reinforced concrete were given positive performance ratings due to design capabilities to prevent cracking. However, proper subbase preparation must not be neglected for these materials.

4.4.1.7 Side-slope stability. Side-slope stability relates to the maximum grade at which a material can be placed. Spray asphalt and synthetic membranes require a lesser slope than the hydraulic asphalt and concrete. Hydraulic asphalt may be placed at a slope up to 2 1/2:1 using special equipment, and concrete can be placed on vertical slopes using forming and guniting. Synthetic membranes perform best on slopes of 3:1 or less.

4.4.1.8 Ability to discourage rodent burrowing. Rigid covers, such as concrete, and hydraulic asphalt concrete, stand up well against animal traffic of all kinds; thinner membranes, however, do not perform as well and require supplemental protection. There are two types of hazards involved; large animals that do mechanical damage to thin membranes because of their great weight and sharp hooves, and small animals that cause damage associated with their search for food and water (burrowing).

Hoofed animals, such as cattle, deer, or horses can easily damage synthetic membranes unless the membrane is covered by a protective layer such as soil. Just how much damage they will do

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depends on the slope of the sidewalls and the firmness of the subgrade. Smaller animals such as gophers, beavers, rats, muskrats, prairie dogs, and mice will attack covers for two reasons:

(a) They may be attracted to them because of the smell or attractive taste.
(b) The cover may be blocking their natural path for food or water.

In the latter case, the behavior of the animal will depend on the accessibility of alternate food routes. If no alternate paths exist, most animals of this class will cut through any cover system for survival. For instance, rats trapped from their food source can cut through concrete, glass, or aluminum; of course, thin plastic or soil membranes offer absolutely no resistance to them. Damage from these causes is not common, but it does occur occasionally (Haxo, 1980).

The potential problem of animal-related damage is most directly related to cap systems, and adequate protection must be incorporated into the design. This protection may include geotextiles, thick soil layers, and stone or gravel layers.

4.4.1.9 Ease of construction. All of the containment materials evaluated are practical materials for in-situ closure construction work. However, certain construction techniques are simpler than others. Synthetic, hydraulic asphalt and reinforced concrete containment construction were given lower performance ratings because of the more complex construction requirements as compared to spray asphalt. These construction aspects include seaming, subbase preparation, specialized equipment for placement, and reinforcement. It must be noted that all of these materials are considered viable from a constructability standpoint.

4.4.1.10 Ability to impede plant root penetration. Root penetration is a potential failure mechanism in the destruction of impermeable containment systems unless they are properly protected and maintained. Woody plants can have root systems that penetrate to depths of 1.5 meters. Damage to cover systems by root penetration is related directly to cover thickness and can be avoided by proper design. Design measures can include the use of biocides, thick cover layers, periodic mowing and time-release biocides. Synthetic membranes and spray asphalts due to their thinness and known inability to resist root penetration, were given lower performance ratings. Only concrete and hydraulic asphalt were given positive performance ratings due to their high structural and hydraulic stability.

4.4.1.11 Compatibility with lagoon wastes. At the present time, there have been very few long-term tests of containment material compatibility with hazardous and explosive wastes. Short-term tests to predict long-term performance are being developed and carried out in the laboratory, but the accuracy of these accelerated tests to reflect long-term stability is unknown (Price et al., 1981).

Gibbons et al. (1983) recently performed laboratory tests to evaluate several synthetic polymer membranes for compatibility with explosive lagoon wastes. The results of the study are presented in Table 13. In general, synthetic membranes were found to be potentially compatible with explosives materials, however, most membranes failed when exposed to the organic solvent TCE. These results indicate that synthetic polymer membranes would only be useful for containment of lagoon wastes with low concentrations of organic solvents. Therefore, the applicability of these materials for lagoon closure appears to be somewhat limited.

No information is available on the compatibility of asphaltics or concrete with lagoon wastes.

Present design philosophy emphasizes the integrity of a cover/cap system to minimize infiltration, and, as a result, leachate is generated. By minimizing or eliminating leachate generation, the issue of waste and leachate compatibility with the liner can be partially resolved. If infiltration is allowed to continue through the cover, however, leachate will be generated and compatibility becomes more important.

In addition to an effective cover system, a protective layer of soil or other material (cushion layer) is generally placed between the waste and the cap or liner material. In this manner the cap or liner is not in direct contact with the waste, and this affords some measure of protection.

The issue of compatibility cannot be overlooked and must be considered when selecting a liner or cap material.

4.5 Site planning design, and construction considerations. The construction and maintenance of a waste containment area can be greatly influenced by local site conditions. Table 14 is a list of factors that should be considered in the site planning and design process.

TABLE 13. SUMMARY OF INITIAL SCREENING TEST RESULTS -- LINER COMPATIBILITY WITH EXPLOSIVE WASTES

Liner group	Relative effect of test chemical[a]		
	TCE	TNT	RDX
PVC	4	3	3
CPE/hypalon	5	3	2
XR-5	5	2	2
HDPE (high density polyethylene)	3	1	1
EPDM/neoprene	4	2	2

[a]Relative effects are ranked from 1 (minimal) to 5 (failure).

Source: Gibbons et al., 1983.

TABLE 14.   FACTORS TO BE CONSIDERED IN THE SITE PLANNING/
DESIGN AND CONSTRUCTION PROCESS (Adapted from
Matrecon, 1980)

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1. Characteristics of the waste to be contained

2. Characteristics (type, texture and depth) of in-situ
    soil materials.

3. Availability of soil material and characteristics of
    the soil.

4. Subgrade characteristics - as determined by soil
    borings.

5. Desired design for bottom and side surfaces.

6. Location and type of bedrock.

7. Location and characteristics of groundwater table.

8. Stability of waste materials and subsurface.

9. Surface drainage and erosion control plans.

10. Local climatic and precipitation conditions.

11. Wind direction and velocity.

12. Ambient temperature.

13. Local vegetation and weed control.

Construction considerations for surface caps are outlined in Section 3, and also are covered in detail by Matrecon (1980).

Basic design and construction guidelines for the installation of nonsoil liners are highlighted in the subsections that follow (Schultz, 1982).

4.5.1 Sprayed-on liners (spray asphalt). Basic guidelines for the installation of sprayed-on liners are as follows:

(a) The subgrade must be compacted, smooth, and free of large rocks, roots, vegetation or other debris.

(b) Provisions for gas venting (venting of any gas build-up that could occur under the liner) and soil sterilization should be made.

(c) Support fabric (geotextile) should be placed on the subgrade with a minimum 6-inch overlap at the seams.

(d) Premix should be blended with an activator and sprayed onto the fabric mat. This step must be completed when ambient temperatures are greater than 60°F.

(e) Spraying should be uniform with overlapping spray patterns and continue until the membrane is at least 50 mils thick. The fabric must be saturated completely by the asphalt in order to produce a complete seal.

(f) At the top of side slopes, the mat should be extended into an anchor trench and backfilled after the asphalt has cured.

(g) Some type of protective cover over the liner is recommended if the liner will be exposed to direct sunlight and otherwise unprotected.

4.5.2 Asphalt concrete. Basic guidelines for the installation of asphalt concrete liners are as follows:

(a) The subgrade must be free of large rocks, roots, vegetation, or other debris.

(b) Subgrades must be smooth, flat, and stable. The subgrade should be rolled with a vibratory roller or similar equipment to fabricate a suitable surface.

(c) The top 6-inches of subgrade should be compacted to 95 percent of the maximum proctor density.

(d) A herbicide should be applied.

(e) Asphalt concrete should be applied and allowed to cure. The applied surface should be smooth and have a consistent minimum thickness of 2 to 3 inches. Two applications, 1-1 1/2 inches thick, should be considered by placing the second application over the first with staggered construction joints; staggered joints enhance tightness, impermeability, and strength.

(f) Application and placement of any asphaltic concrete liner should be planned to avoid cold joints. If cold joints cannot be avoided, they should be heated prior to forming a new joint.

(g) Compaction by rolling is required immediately after placement.

(h) After compaction, a hot asphalt surface seal may be applied.

4.5.3 Polymer membranes. Basic guidelines for the installation of polymer membranes are as follows:

(a) Subgrades should be smooth and free of sharp rocks or vegetation that could cause punctures. Rolling and compaction is recommended.

(b) Dry and warm weather conditions are important to enhance field seaming of sheets.

(c) Membranes must be secured at the top of any slopes. The recommended securing technique is to place the edge of the membrane in an earthen trench and backfill the trench with soil.

(d) Proper sealing around any penetrations (such as leachate collection and piping systems) must be accomplished using appropriate adhesive sealing compounds.

(e) Field inspection and testing of seams is required.

Other polymer membrane installation factors such as field seaming, required weather conditions, and installation procedures are membrane-specific and site-specific. General installation parameters for various types of membranes are presented in Table 15.

4.5.4 Leachate collection. Depending on the cap design and the local climatic conditions, a leachate collection system may be required to prevent a "bath tub" effect. A nonsoil, impermeable liner will not allow all liquids to pass into the underlying soils. As a result, any liquid or infiltration that enters through the cap/cover will be collected by the liner and accumulate. Unless provision is made to remove this accumulated

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TABLE 15. GENERAL POLYMERIC MEMBRANE INSTALLATION PARAMETERS

Liner type	Adhesive system used	Field seam width range (inches)	Field overlap range (inches)	Minimum suggested material temperature (F^O)	Cover[a]
Chlorinated polyethylene (CPE)	Bodied solvent, solvent welded	2	6-12	60	Not required
Chlorosulfonated polyethylene (CSPE)	Bodied solvent, heat, solvent welded	2-4	2-6	60	Not required
Ethylene propylene rubber (EPDM)	Contact adhesive	2-4	4-6	60	Not required
Polyethylene high-density (HDPE)	Heat welded	1	4-8	60	Not required
Polyvinyl chloride (PVC)	Solvent welded, heat welded	2-4	2-6	60	Required
Neoprene	Contact adhesive	2-4	6-12	60	Not required

[a]Usually recommended by most manufacturers.

Source: Shultz et al., 1982.

liquid, a bath tub effect will occur and leachate will tend to escape over the liner, resulting in failure of the containment system.

Conditions that will result in water entering the containment area by means of infiltration include the following:

(a) Climatic conditions where there is a net annual infiltration rate (precipitation exceeds evaporation and other losses).
(b) The cap system is not totally impermeable.
(c) The cap system is damaged thereby allowing water to enter.

A leachate collection system is designed to allow removal of the water/leachate that collects in the liner system. This can be a semi-active system that requires periodic pumping to remove leachate from the containment area. Other systems utilize a gravity drain to a storage tank for leachate; the tank would then be pumped out periodically.

To minimize the quantity of leachate generation when using an impermeable liner, the cap system should also utilize an impermeable nonsoil material. This is particularly important for those climatic conditions where there is a net-annual infiltration rate.

Figure 28 depicts a typical design concept for a nonsoil liner system with leachate collection. Several important elements of this design concept include the following:

(a) Liner system placed on a prepared subbase.
(b) Porous layer placed over the liner to facilitate leachate collection and protect the liner.
(c) Piping for leachate collection and removal.
(d) Impermeable cap.
(e) Final cover system placed over the cap.

The porous leachate collection layer is typically composed of sand or gravel and is 1 to 2 feet in thickness. Leachate removal piping is typically perforated PVC in the collection zone and may be 4 to 6 inches in diameter. For the system shown on Figure 28 a pump would be required to remove any collected leachate.
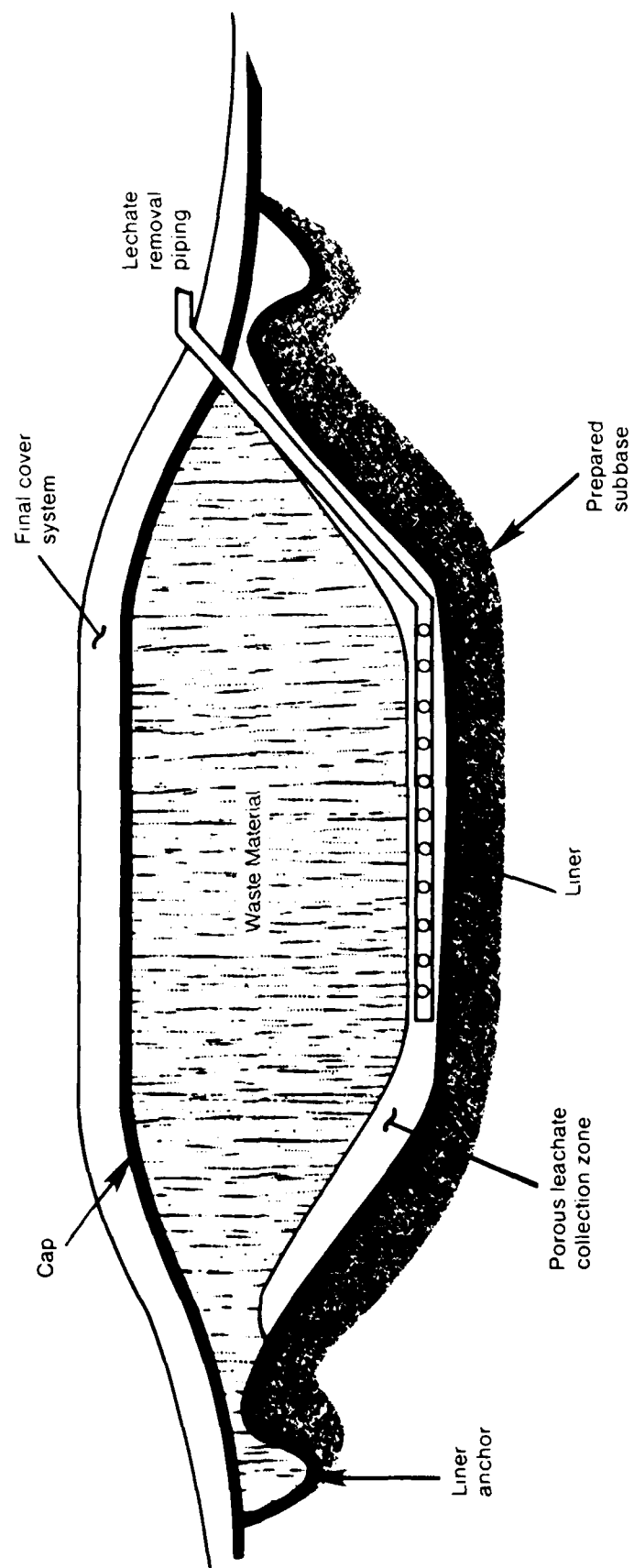
Figure 28. Nonsoil liner with leachate collection.

Lechate removal piping

Final cover system

Prepared subbase

Waste Material

Cap

Liner

Porous leachate collection zone

Liner anchor

In some cases, a double liner system may be considered. This concept is shown on Figure 29. The primary design objectives for a double liner system are to provide the following:

(a) Provide a back-up to the primary liner in the event of failure or leakage.
(b) Provide a method for monitoring under the primary liner as an early warning leak detection system.

The porous collection zone overlying the secondary liner normally serves as a monitoring area. Any liquid that collects above the secondary liner can be sampled and tested for the presence of any contaminants. This serves as an effective verification method for the primary liner system.

4.6 **Performance verification**. Strict quality control during construction of impermeable waste containment areas is of fundamental importance to assure proper functioning of impermeable surfaces. Observations must be made to ascertain that design specifications are strictly followed during construction. For membranes, seams must be checked for proper sealing and the membrane must be inspected for tears or holes. Poured, or sprayed seals must be checked for cracks or holes, and sufficient thickness of the seal.

Post-construction performance verification for caps or surface seals consists of visual inspection and lysimeter tests.

For liners, groundwater monitoring or a secondary liner system may be used for verification. Remote sensing techniques such as high frequency pulse techniques, electromagnetics, resistivity, or seismic techniques may also be employed for performance verification. However, the use of these remote-sensing techniques for leak detection in subsurface liners has not been proven totally reliable (Waller et al., 1982).

4.7 **Costs**. The cost of waste containment facilities varies depending on site location and individual site characteristics. The estimated unit costs for nonsoil materials and sealing methods are presented in Table 16. Table 17 is a list of factors which affect costs that can vary from site to site.

The use of a liner system will probably include the costs for waste excavation so that a liner can be constructed and waste reburied. Typicaly, the lined area would be constructed in an area somewhat adjacent to the lagoon and the waste relocated.
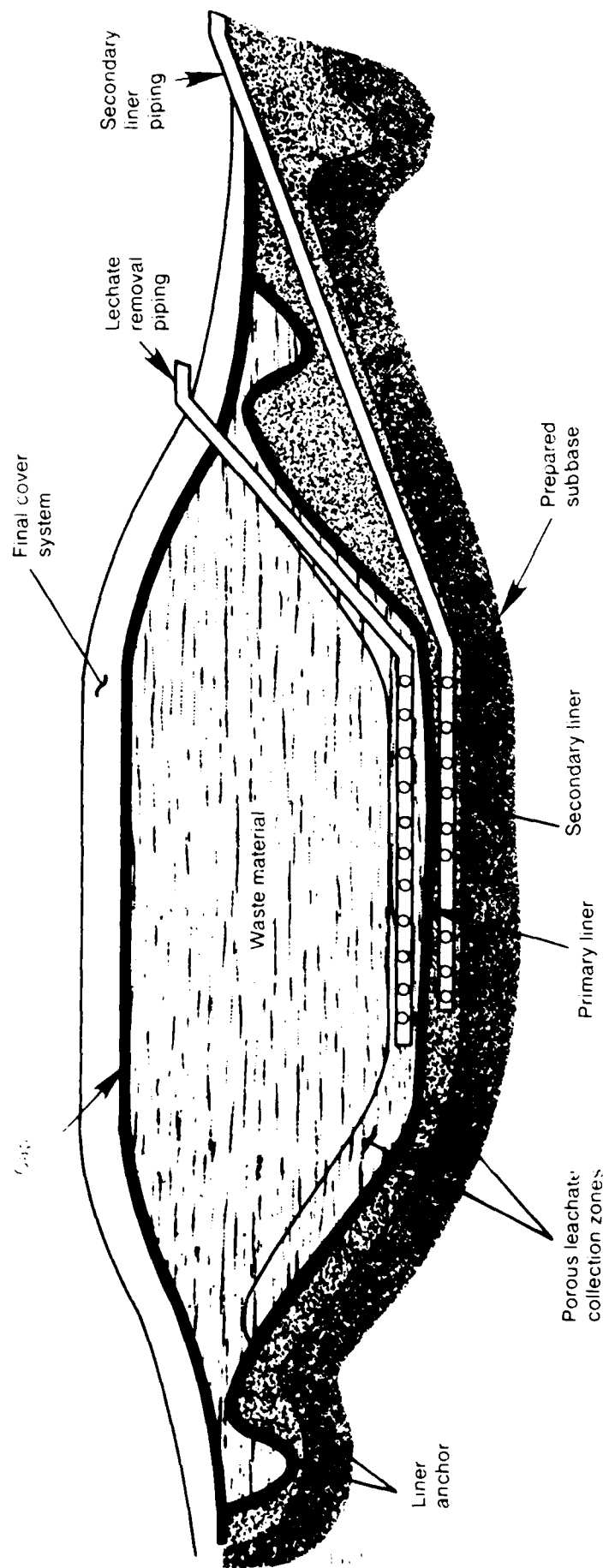
Figure 29. Nonsoil liner with leachate collection - double liner system.

TABLE 16. ESTIMATED UNIT COSTS FOR NONSOIL SEALING METHOI
AND MATERIALS (Adapted from EPA, 1982)

Cover material and/or method of installation	Unit co
Cement concrete (4 to 6 inch layer), mixed, spread compacted onsite	$6-10/:
Asphalt concrete (4 to 6 inch layer), including base layer	$3-5/s<
Sprayed asphalt membrane (1/4 inch layer and soil cover), installed	$2-3/s<
PVC membrane (20 mil), installed	$1-2/s<
Chlorinated PE membrane (20-30 mil), installed	$2-3/s<
Ethylene interpolymer alloy membrane, installed	$3-4/s<
Hypalon membrane, (30 mil), installed	$7/sq \
Neoprene membrane, installed	$5/sq \
Ethylene propylene rubber membrane, installed	$3-4/s<
Butyl rubber membrane, installed	$3-4/s<

TABLE 17.   COST ITEMS RELEVANT TO WASTE CONTAINMENT
            FACILITIES

---

1.   Cost of materials delivered to the site.

2.   Site preparation:

     a.   Rough grading
     b.   Subgrade preparation
     c.   Compaction
     d.   Surface smoothing

3.   Costs associated with installation of sealant
     materials:

     a.   Special structures adaptation
     b.   Anchoring
     c.   Field seaming
     d.   Quality control testing

4.   Groundwater monitoring systems, if necessary, only at
     lining interface.

5.   Soil cover costs.

6.   Liner/cover costs.

7.   Leachate control system.

8.   Leachate collection and treatment.

9.   Gas control system.

Source: Matrecon, 1980.

4.8 <u>Applicability and limitations.</u> The applicability and limitations of nonsoil covers as a means of in-place closure of inactive waste lagoons are conceptually similar to respective issues of soil cover systems (subsection 3.7). Additional applicability and limitation issues include the following:

(a) The longevity of nonsoil covers is questionable for the following reasons:

- Synthetic materials have been used as liners and covers for only short periods of time.
- Some synthetic materials tend to lose plasticizer and become brittle and subject to cracking.
- The mechanical properties of synthetic materials may degrade over long periods of time.
- Rigid cover systems (e.g., concrete) may fail due to the instability of the waste material itself.

(b) The compatibility of the cover materials with waste components is questionable, especially over long periods of time.

(c) Nonsoil materials are not sufficient as a cover system. An additional soil cover layer will be required to protect synthetic or rigid materials.

(d) Nonsoil materials may be subject to massive failure (e.g., cracking) and may cause a catastrophic release of contaminants to the environment.

These limitations may reduce the potential applicability of non-soil materials for long-term in-place closure of lagoons. However, nonsoil materials may be applicable as interim remedial-action measures or in conjunction with other measures that promote long-term durability.

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5. SURFACE-WATER DIVERSION

5.1 **Introduction.** Surface-water diversion techniques may be applied to in-situ lagoon closure plans to help provide long-term stability of a closure site. Surface-water diversion is rarely, if ever, the only remedial measure taken at a lagoon site. Normally, surface-water control is used in conjunction with other remedial measures such as surface sealing, ground-water management, and/or waste treatment, in an integrated closure plan.

The primary objective of surface-water diversion is to hydrologically isolate a closed lagoon from surface-water inputs, and thereby reduce the potential for leachate generation and damage to other engineering control measures such as erosion of cover materials. Several well-established surface-water control methods are applicable to lagoon closure. Common methods include site grading and use of diversions or terraces. These methods are briefly discussed in the subsections that follow.

5.1.1 **Grading.** Grading is a broad term used to describe techniques commonly used in the construction industry to reshape existing land surfaces. Grading can be used during site closure as a surface-water runoff and erosion control measure. Excavation, hauling, spreading, and soil compaction are the major elements of a complete grading operation. Heavy construction equipment is required for these operations.

The overall design objective of grading is to accommodate rapid, yet controlled, surface-water runoff, while minimizing the potential for soil erosion. Short runoff areas are desired with side slopes steep enough to promote rapid drainage, yet not excessively steep so that water runoff causes erosion.

Specific design criteria for grading varies from site-to-site depending on local topography, hydrology, climate, soil characteristics, and future land use plans. Some fundamental design guidelines for grading are outlined in subsection 5.2.

5.1.2 **Diversions.** Diversions are drainageways that are constructed along the contours of graded slopes with an earthen dike on the downhill side of the drainageway. Schematics of two types of diversions are presented on Figure 30, showing typical dimensions and basic design features.

Trapezoidal cross-section

Parabolic cross-section
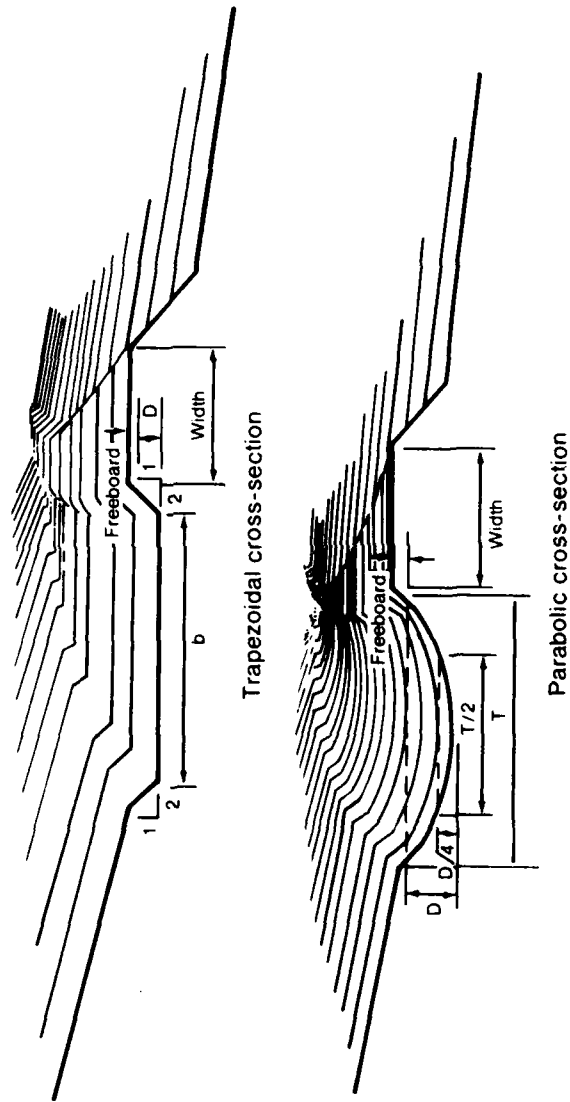
Source: U.S. Department of Agriculture Soil Conservation Service,
College Park, Maryland

Figure 30. Two types of diversions.

The purpose of a diversion is to intercept and convey runoff to stable outlets at nonerosive velocities. Diversions may be used in the vicinity of closure sites to direct surface water from higher elevations away from the closed lagoon area. This practice is commonly referred to as "diversion of run-on." At closure sites with earthern caps covering a large surface area, diversions may be built across long slopes to divide the slope into shorter nonerosive segments.

5.1.3 Terraces. Terraces are wide, flat, or gently-sloping areas that can be constructed along the contour of very long or steep slopes at closure sites to slow down runoff water and prevent erosion. Terraces usually direct water into diversions for offsite transport. Common design configurations for terraces are depicted on Figures 31 and 32. This type of terracing could be incorporated into a final cover design or design for major berms or dikes.

5.2 Environmental considerations. Surface-water diversion structures must be designed on a site-by-site basis considering local environmental conditions. Environmental factors that influence the final design include local topography, hydrology, climate, soil characteristics, and site land-use plans. In addtion to environmental factors, the design must be compatible with the other engineering control measures being implemented at a site. Factors that must be considered include the following:

(a) Final site topography and grading plan.
(b) Overall drainage plan for the site and surrounding area.
(c) Final cover system.
(d) Site access.
(e) Final site use.

Detailed methods for designing these structures can be found in surface hydraulics texts. General design guidelines are listed in Tables 18, and 19, and 20.

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Swale or ditch

1-2% Slope

Terrace

Swale or ditch

1-2% Slope
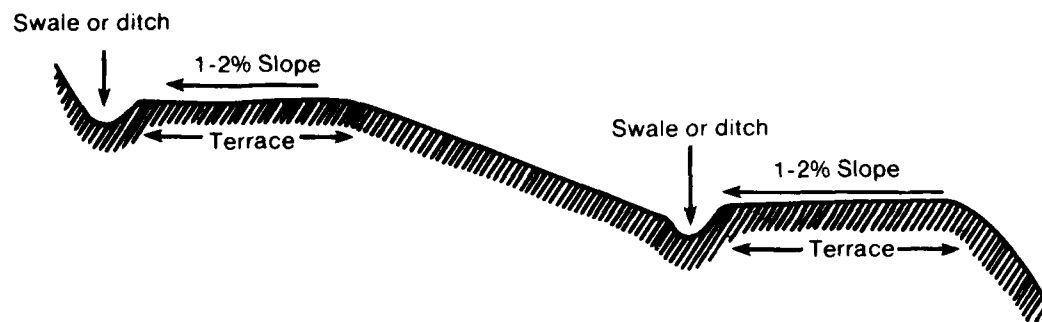
Terrace

a. Terraces with reserve fall

Diversion

Slope

Terrace

Berm
or
Dike

Diversion

Slope

Terrace

Berm
or
Dike
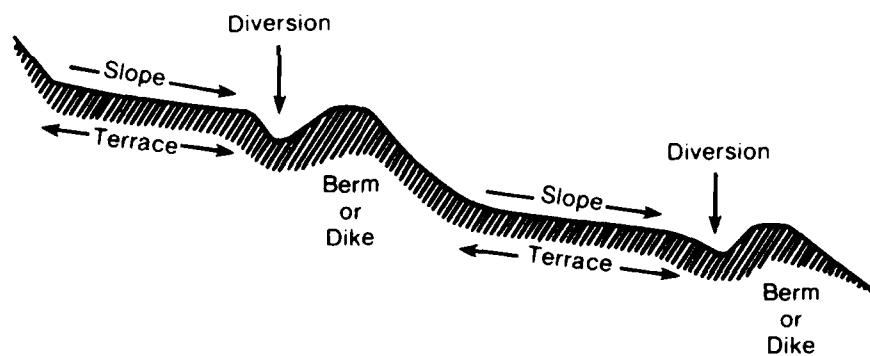
b. Terraces with natural fall

Source: EPA, 1982

Figure 31. Common design configurations.
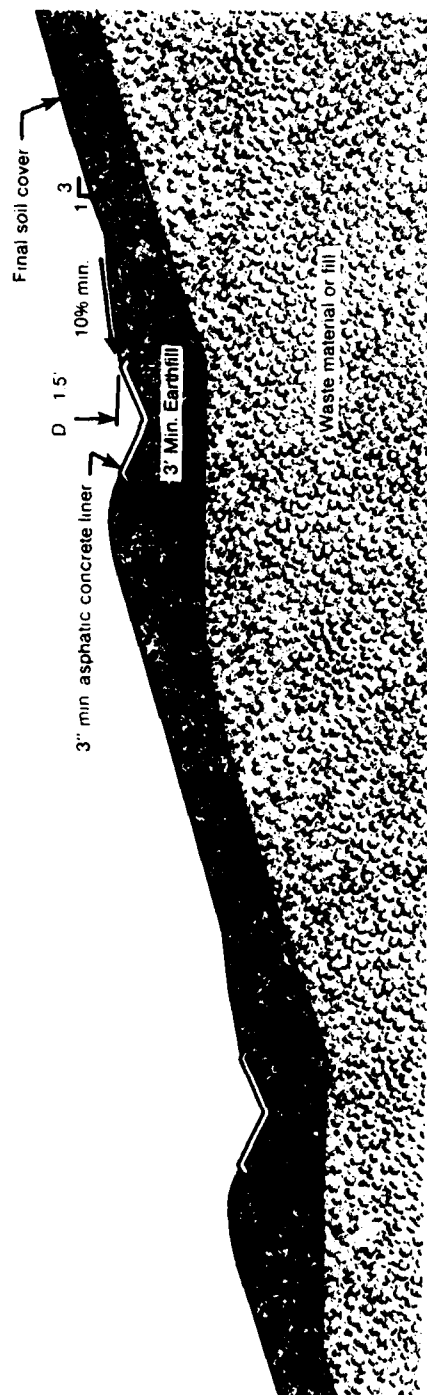
Figure 32. Typical terrace.

Source: EPA. 1982

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TABLE 18. GRADING -- FUNDAMENTAL DESIGN GUIDELINES IN
           CLOSURE OF HAZARDOUS WASTE DISPOSAL SITES (EPA,
           1982)

---

1. In general, a disposal or lagoon area being closed
    should be graded so that the center of the site is at
    the highest local elevation.

2. Fill material used for regrading should be compacted
    to prevent excessive future settlement.

3. As part of the final cover and grading plan, top slopes
    of closed lagoon areas should be graded from 5 to 12
    percent to promote runoff but never greater than 18
    percent.

4. Slope length should be minimized; terraces and diver-
    sions can be used.

5. Side slopes of berms, dikes, and final covers should
    not be constructed at a slope exceeding 3:1.

6. Soils used to cover graded slopes should be selected
    on the basis of shear strength and erodibility. Clayey
    soils with high organic contents are the most desira-
    ble. Sandy and silty soils are erodible and should be
    avoided if possible. The soils and slopes should be
    properly stabilized to prevent erosion damage.

TABLE 19. DIVERSIONS -- GENERAL DESIGN AND CONSTRUCTION
CRITERIA (EPA, 1982)

1. Diversion location is determined on the basis of outlet conditions, topography, soil type, slope length, and grade.

2. Diversions should have the capacity to carry the peak discharge from a 25-year design storm.

3. A diversion channel should generally be parabolic or trapezoidal in shape, with side slopes no steeper than 2:1, preferably 3:1.

4. The supporting dike or berm should have a minimum width at the base of 5 feet; freeboard should be 6 inches minimum over the peak water level in the channel.

5. Each diversion should have a stable outlet such as a natural waterway, stabilized open channel, chute, or downpipe.

6. The diversion should be adequately stabilized to handle expected peak flow velocities. For design velocities <3.5 ft/sec, seeding and mulching for vegetative establishment is generally adequate; for velocities >3.5 ft/sec, stabilization with sod or with seeding protected by jute or excelsior matting should be considered. Rip-rap or stone lining of a diversion may be required to handle veolcities >3.5 ft/sec in some cases.

7. For diversions or drainage channels that carry flow during dry weather (base flow) due to groundwater discharge or delayed subsurface runoff, the bottom should be protected with a stone center; subsurface drainage with gravel/stone trenches may be required where the water table is at or near the surface of the channel bottom.

8. Any fill that is required to construct the diversion should be compacted to minimize the potential for washout or settlement.

9. All debris, brush, stumps, excess sediment accumulation, and other obstructions will be cleared to prevent improper functioning of the diversion.

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TABLE 20.   TERRACES -- GENERAL DESIGN GUIDELINES (EPA, 1982)

---

1.   The width and spacing between terraces will depend on slope steepness, soil type, and slope length.

In general:

1.   For slopes greater than 10 percent, one terrace per every 10-foot rise in elevation should be considered.

2.   For slopes greater than 20 percent, one terrace per every 20-foot rise in elevation should be considered.

3.   Terraces should be designed with sufficient width and height to withstand a 24-hour, 25-year storm event.

4.   The terrace and diversion/drainage channel should be stabilized to handle expected velocities and flow conditions. Generally, vegetative stabilization will be adequate, however, some areas may require riprap or rock.

5.3 **Economic considerations.** A systematic approach to estimating costs for construction of surface-water control structures is outlined in Table 21.

Approximate unit costs associated with grading and surface-water diversion structures are presented in Tables 22 and 23, respectively.

5.4 **Environmental performance verification.** Environmental performance verification of surface-water diversion structures consists primarily of the following measures:

(a) Quality control/construction management.
(b) Post-construction inspections.

Quality control/construction management is necessary to ensure that all design specifications are met during construction of diversion structures. Typical elements of a quality control program include site surveying, soil testing, and visual inspections. All surfaces should be checked for proper compaction and accurate grade levels. Concrete and asphalt, if used, must be poured/constructed according to design specifications. Subgrades must be inspected for stability, and all construction materials must be checked to ensure that they conform to design specifications. Details on soil testing are discussed in Section 3 for cover systems; some of these tests will apply for diversion structures (e.g., soil classification, sieve analysis, organic content, proctor test, etc.).

Post-construction inspection of surface-water diversion structures consists primarily of periodic visual inspections. Any cracks, erosion damage, or malfunctions should be noted and corrected. Periodic maintenance should be performed as necessary.

5.5 **Limitations.** Surface-water management is often a necessary element of in-place closure of inactive lagoons. This remedial action concept is often cost-effective and provides a reasonable level of protection with respect to surface-water and groundwater quality. Some of the limitations of surface-water management technology include the following:

(a) Surface-water management is usually not sufficient for remedial action. However, it often is applied in combination with other in-place closure techniques (e.g., cover systems) to form a cost-effective remedial-action approach.
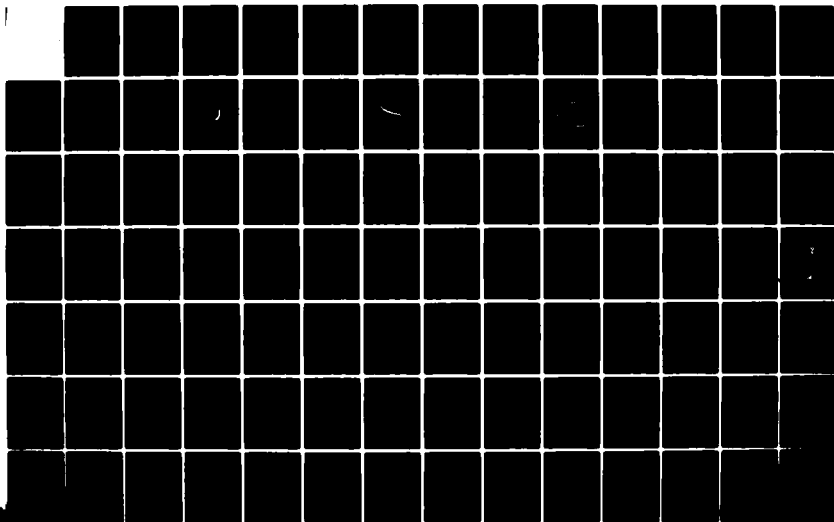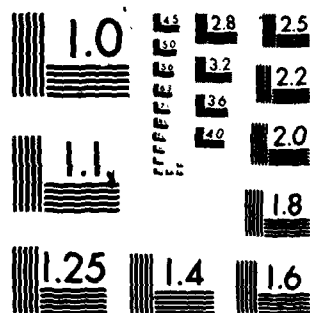
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

TABLE 21. SYSTEMATIC APPROACH TO ESTIMATING COSTS FOR
SURFACE-WATER CONTROL STRUCTURES (EPA, 1982)

1. Determine source of required earth fill; onsite vs.
    off-site, and hauling distances.

2. Determine amount and type of soil fill required for re-
    grading, construction of terraces, and dikes or berms,
    and associated costs.

3. Determine type and quantity of other materials required
    (concrete, asphalt, riprap, stone, etc.) and associated
    costs.

4. Determine installation or construction costs.

5. Determine costs of required stabilization (e.g., seed-
    ing, riprap, matting) for earthen structures.

6. Determine estimated maintenance and repair costs that
    will be incurred until the control measures are ade-
    quately stabilized.

7. Total costs of items 1 through 6.

TABLE 22.   UNIT COSTS ASSOCIATED WITH GRADING COVERED
DISPOSAL SITES (Adapted from EPA, 1982)

Description	Approximate unit cost
Topsoil (sandy loam), hauling, spreading, and grading (within 20 miles); labor, materials, and equipment	$15.00/cu yd[a]
Onsite excavation, hauling, spreading, and compacting earth (1,000- to 5,000-foot haul); labor and equipment	$1.00 - 2.00/cu yd[b]
Loam topsoil; material only	$5.00/cu yd[b]
Excavate, haul 2 miles, spread and and compact loam, sand, or loose gravel (with front end loader); labor and equipment only	$1.75 - 2.00/cu yd
Grading site excavation and till (no compaction) 75-hp dozer, 300-foot haul 300-hp dozer, 300-foot haul	$2.00 - 2.50/cu yd[c] $1.50 - 2.00/cu yd[c]
Testing soils for compaction	$25.00 - 30.00/sample[b]

[a]Haseley Trucking Company, 1980.
[b]McMahon and Pereira, 1979.
[c]Godfrey, 1979.

TABLE 23.   UNIT COSTS ASSOCIATED WITH SURFACE-WATER
DIVERSION AND COLLECTION STRUCTURES (Adapted
from EPA, 1982)

Description	Approximate unit cost
Trench excavation:	
Loam, sand, and loose gravel --	
1 ft - 6 ft deep, 1/2:1 sides	$0.50 - 0.75 cu yd
6 ft - 10 ft deep	$0.50 to 0.60/cu yd
Compacted gravel and till --	
1 ft - 6 ft deep, 1/2:1 sides	$0.50 - 0.75/cu yd
6 ft - 10 ft deep	$0.25 - 0.50/cu yd
Building embankments; spreading, shaping, compacting;	
material delivered by scraper	$0.25 - 0.50/cu yd
material delivered by back dump	$0.50 - 0.75/cu yd
Loose gravel, excavation, loading, hauling 5 miles, spread and compacting	$4.00 - 4.50/cu yd
Stone riprap; dumped from trucks, machine-placed	$15.00 - 20.00/cu yd
Soil testing:	
Liquid and plastic limits	$35/test
Hydrometer analysis; specific gravity	$60/test
Moisture content	$10/test
Permeability	$50/test
Proctor compaction	$40 - 50/test
Shear tests, triaxial	$200 - 350/test
direct shear	$75 - 225/test

(b) Long-term integrity of surface-water management devices is questionable due to erosion, silt buildup, and plant growth.

(c) Although surface-water management is considered a "passive" element of remedial action, some level of maintenance is required to keep it functional for long periods of time.

(d) Most of the processes do not lend themselves readily to in-place application.

(e) Safety issues may limit the application of some of the processes. Materials handling, heat, or incompatibility may cause explosion and other hazards.

(f) Those processes that have to be completed in aqueous form may result in producing leachate or wastewater effluents.

(g) Some of the processes result in generation of more toxic soluble by-products and/or toxic fumes and other unknown residuals.

(h) Further research is needed before treatment can be used as a means of in-place closure of inactive waste lagoons. Areas of concern include the following:

- Treatability of mixed wastes representative of lagoon contents.
- Determination of reaction kinetics.
- Characterization of soluble and gaseous by-products.
- Evaluation of materials handling systems.
- Demonstration of the most promising technology in a pilot plant, full-scale operation.

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6. ENVIRONMENTAL ISOLATION TECHNIQUES

6.1 <u>Description</u>. Environmental isolation techniques are in-situ closure measures that isolate a lagoon from the subsurface environment. In general, these measures are directed toward the control of groundwater and can include the collection or containment of contaminated groundwater as a leachate plume or diversion/manipulation of clean groundwater. These groundwater control techniques are divided into two broad categories as follows:

(a) Groundwater diversion - passive controls.
(b) Groundwater manipulation - active controls (see Section 7).

Diversion control measures are essentially "passive" techniques which require little or no long-term operating requirements. Once in-place, these controls will continue to function with minimal or no operating support such as utilities or personnel. The manipulation measures involve active components such as pumps, maintenance, discharge piping, possible treatment systems, or utilities.

These two broad types of control categories are not mutually exclusive, and techniques for both categories may be combined into an overall environmental isolation system. For example, an active control such as extraction (groundwater pumping) could be used with a passive technique such as a slurry wall to provide a very effective isolation system. The objective is to make maximum use of the advantages of both techniques in designing the most effective overall system.

6.2 <u>Groundwater diversion</u>. Groundwater diversion technologies are subsurface control measures essentially designed to divert the flow of groundwater or contain a leachate plume. The primary objective of these measures is not to effect significant changes in the water table elevations, such as raising or lowering the water table, but to redirect or divert the flow of groundwater around a lagoon area or contain leachate/contaminated groundwater under a lagoon. The successful use of these measures is, of course, dependent upon the specific hydrogeologic and soil conditions of the site.

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6.3 Slurry walls/cutoff walls.

6.3.1 Process description. The use of slurry walls (also called cutoff walls) was originated in the mid-1940's for the oil industry and has increased during the last two decades (Gill, 1980) with many applications in the construction industry. The use of slurry walls included applications as foundation and embankment cutoffs for water-retaining structures and to control seepage into excavations for dewatering purposes. More recently, slurry walls have been employed to prevent migration of liquid waste in the groundwater and to contain leachate from solid and hazardous waste sites. Advances in technology have enabled the construction of low permeability cutoff walls that remain stable in contaminated environments and resist attack by wastes and contaminated groundwater (D'Appolonia, 1980).

In general, slurry trenching involves excavating a narrow trench (usually over 3 feet wide) through a pervious deposit and connecting into a low permeability zone aquiclude. Shallow trenches are normally excavated with backhoe equipment, while for greater depth, excavation is performed by clam shell. The sides of the trench are supported and protected from collapsing by keeping the trench filled with a bentonite slurry during excavation and prior to backfilling. The primary function of the bentonite slurry is to maintain the stability of the trench wall during excavation until the trench can be backfilled with lower permeability material.

The slurry used in trenching operations is generally a 4 to 7 percent suspension of bentonite in water (Boyes, 1975). Excavation of a trench under a bentonite slurry allows the following to happen:

(a) The slurry acts as shoring, supporting the trench walls to prevent cave-in and slumping during excavation.
(b) The weight of the slurry forces bentonite to penetrate the voids in the soil matrix on the inner trench walls and bottoms.

The latter effect causes the sides and the bottoms of the trench to be lined with a layer of bentonite (filter cake), thereby reducing the permeability (U.S. EPA, 1982).

When the section of a trench has been excavated to the desired depth, backfilling follows, often at one section of a trench while a new section is being excavated. Several media can be used for backfilling the trench including the following:

(a) Soil/bentonite mixture.
(b) Cement/bentonite mixture.
(c) Reinforced concrete.

Soil/bentonite cutoff walls are formed by mixing small amounts of bentonite slurry from the trench with needed soils. Cement-bentonite cutoff walls are excavated using a slurry of portland cement and bentonite that is left to set, forming the final wall. In general, soil/bentonite cutoff walls have the wider application range for environmental rehabilitation of inactive waste disposal sites because of their low permeability, wide range of waste compatibility, and lower cost. However, they require a large work area, flat topography, and exhibit lower structural strength (higher elasticity).

For most applications a slurry wall must be connected (keyed) to a low permeability stratum (aquiclude) or a competent geological member (bedrock) in order to have an effective groundwater diversion or isolation of waste or leachate plume. In a few cases, however, nonkeyed (hanging) slurry walls may be used to isolate or recover lower density immiscible fluids, such as hydrocarbons and petroleum products, that could remain floating at the upper layers of groundwater.

Slurry wall techniques may have some merit in remedial action projects for inactive waste lagoons. After proper site characterization, design, and construction, a slurry wall could provide one or a combination of the following benefits:

(a) Diversion of groundwater around the lagoons or contaminated area.
(b) Containment of leachate plume in the vicinity of the lagoon.
(c) Attenuation of contaminants present in leachate plume by using the ion exchange capacity of the slurry wall material.

It should be emphasized, however, that slurry cutoff walls are applicable only to specific situations where site characteristics allow proper isolation of the waste or the contaminants, and should not be viewed as a universal answer to all lagoon site areas. Moreover, slurry walls will rarely, if ever, be the only remedial measure applied to a lagoon area. They are usually accompanied by other remediation measures, such as surface sealing, active or passive groundwater management, waste treatment, or waste removal.

Slurry wall construction utilizes common earth moving and excavation techniques and commercially available equipment and materials. Trenches as deep as 50 feet could be excavated using hydraulic backhoe equipment. Deeper trenches require clamshell excavation equipment. All such equipment is commercially available; however, the unit costs (in $/square foot of slurry wall area) increase drastically with increase in depth over 50 feet. Most applications of isolation of lagoons, therefore, are for those sites where an aquiclude is found within 50 feet below the lagoon area surfaces.

Conceptual applications of slurry walls and control of migration of contaminants from hazardous waste lagoons include the following:

(a) Utilization of slurry walls that are keyed to an aquiclude as a means of capture and recovery of leachate that might be seeping from the lagoons.

(b) Used in conjunction with a lagoon sealing system for passive containment of waste and leachate.

(c) Use of a "hanging" slurry wall for containment and recovery of lightweight immiscible fluid (e.g., petroleum products).

(d) Use of circumferential wall configuration to completely encircle the waste lagoon.

(e) Use of partial slurry wall configuration upgradient from the lagoon to divert groundwater.

(f) Use of downgradient slurry walls to capture and recover contaminated groundwater.

6.3.2 Environmental considerations and constraints.

6.3.2.1 Waste characteristics. The presence of organic and innorganic compounds in the leachate or in the groundwater can have detrimental effects on the bentonite slurry used for construction and admixture with soil to fill the trench. Such contaminants could affect the physical and chemical properties of the bentonite and the slurry wall itself or the backfill material. This may lead to deterioration of the quality of the wall and its long-term effectiveness in containment and isolation of the lagoon area. Such detrimental effects include the following:

(a) Flocculation of the slurry.

(b) Reduction of bentonite swelling capacity.

(c) Structural damage of the bentonite or backfill material.

(d) Increase in permeability in the slurry wall.

The presence of a high concentration of electrolytes, such as sodium, calcium, and heavy metals in the groundwater (Matrecon, 1980), can produce several changes in the bentonite water system that will lead to flocculation or reduced hydration of the bentonite. Monovalent sodium ions on the surface of the bentonite clay can be readily exchanged with multivalent ions, such as calcium or other metal ions, contained in the contaminated groundwater.

Strong organic and inorganic acids and bases can dissolve or alter the bentonite or soil portion of the backfill material, leading to a significant increase in permeability. Aluminum and silicate, two of the major components of bentonite, are readily dissolved by strong acids or bases (Matrecon, 1980). For example, when clays are exposed to acetic acid, significant soil piping occurs due to the solution of the soil components (Anderson, Brown & Green, 1982). This leads to a significant increase in permeability in all clay types, although strong bases usually produce a greater increase in permeability than acids.

Various organic and inorganic compounds can cause a change in the amount of swelling that bentonite particles have undergone. This can lead to increased permeability of the finished slurry wall. The decrease in the amount of swelling of the hydrated bentonite increases the amount of pore space in the backfill, thus increasing the permeability of the wall.

Neutral polar organic compounds can replace the water contained in the clay particle interlayers thus affecting the size of the bentonite particles (Anderson & Brown, 1981). For example, acetone, a neutral polar compound, causes a significant increase in permeability in four types of clay (Anderson, Brown & Green, 1980). In the Anderson study, after contact with the acetone, the clay showed extensive shrinkage and cracking. This soil shrinkage is usually associated with hydration, indicating that the acetone extracted water from the soils surfaces. It should be noted, however, that the concentrations of organic chemicals used in these studies are orders of magnitude in excess of those found in environmental situations. The results, however, indicate what could happen under extreme conditions.

Table 24 gives a qualitative summary of the effect of permeation by various pollutants on the permeability of soil/bentonite backfill mixes containing about 30 to 40 percent fines. Tests should always be conducted using the specific soil materials from the site and the actual pollutant in designing a cutoff. Nevertheless, the results of a large number of experiments on a variety of materials using a range of representative pollutants indicate that a well-graded soil/bentonite material containing more than 30 percent plastic fines and about 1 percent bentonite exhibit only a small increase in permeability when leached with many common contaminants. A permeability increase of a factor of 2 to 4, if considered undesirable, can be reduced by addition of more clay or by increasing the plasticity of the fines contained in the backfill blend. Increasing the clay content will both reduce the initial permeability and the magnitude of the increase (D'Appolonia, 1980).

6.3.2.2 Site conditions. A key to the success of bentonite slurry walls as a means of waste and contaminant isolation depends on the actual site conditions. It is essential to have detailed site characteristics, especially in the areas listed in Table 25.

Knowledge of the geohydrological characteristics of the site is an essential part of selection, design, and construction of a bentonite/slurry cutoff wall, especially in the following areas:

(a) The depth to which the trench and slurry walls will extend.

(b) The type of anchoring (connection) with the aquiclude.

(c) The type of excavation equipment to be used.

(d) The suitability of all soils found on the site for backfilling the trench.

TABLE 24.   SOIL/BENTONITE PERMEABILITY INCREASE DUE TO
LEACHING WITH VARIOUS POLLUTANTS

Pollutant	Soil/bentonite backfill (silty or clayey sand) (30 to 40 percent fines)
CA^{++} or Mg^{++} at 1,000 ppm	N
CA^{++} or MG^{++} at 10,000 ppm	M
NH_4NO_3 at 10,000 ppm	M
Acid (pH>1)	N
Strong acid (pH >1)	M/H[a]
Base (pH <11)	N/M
Strong base (pH>11)	M/H[a]
Benzene	N
Phenol solution	N
Sea Water	N/M
Brine (SG-1.2)	M
Acid mine drainage ($FeSO_4$ pH 3)	N
Lignin (in Ca^{++} solution)	N
Organic residues from pesticide manufacture	N
Alcohol	M/H

[a]Significant dissolution likely.

Key

N = No significant effect; permeability increase by about a
factor of 2 or less at steady state.

M = Moderate effect; permeability increase by factor of 2 to
5 at steady state.

H = Permeability increase by factor of 5 to 10.

I

TABLE 25. SITE DATA FOR SLURRY WALL EVALUATION

1. The groundwater regime including water table depth and flow gradients.

2. Aquifer type (confined and/or unconfined).

3. Groundwater quality and characteristics, including the presence of ionic species that might interfere with the slurry wall characteristics.

4. Soil characteristics including soil type, particle size and distribution, and permeability.

5. Structural attitude and distribution of bedrock and overlying strata below the lagoon site.

6. Presence and depth of aquiclude and low permeability deposit or component bedrock.

7. Weathering of these strata, and evidence of incompetence of rock formation.

8. Chemical and physical properties of geological strata, including mineralogy and permeability.

6.3.3 Process evaluation methodology. The major functional elements of design and construction of a bentonite slurry wall include developing the following design bases:

(a) Slurry preparation and placement.
(b) Trench excavation.
(c) Soil/bentonite backfilling.
(d) Slurry wall connections.

A systematic approach for the evaluation of such elements and other technical and cost considerations are discussed in the following paragraphs.

6.3.3.1 Slurry preparation and placement. Prior to initiating excavation, the slurry must be prepared to be used in the trench construction. The basic functions of the slurry are as follows:

(a) Keep the trench open during excavation.
(b) Form a "filter cake" on the inner trench walls and bottom.
(c) Remain fluid during placement of backfill material.

The quality of the slurry is, therefore, a key element in the stability and success of construction and performance of the cutoff wall. Primary slurry properties considered to be important and typically specified are viscosity, density, filtrate loss, and pH (Millet and Perez, 1981).

In slurry trench practice, viscosity is generally measured with a Marsh funnel. Viscosity is a measurement of the ability of a fluid to resist shearing; a minimum viscosity of approximately 40 Marsh seconds is generally considered appropriate for slurry wall construction (Millet and Perez 1981).

The minimum density of the slurry is normally slightly greater than that of groundwater. The maximum unit weight is typically on the order of 65 pounds/cubic foot - 75 pounds/cubic foot, and is limited to ensure the bentonite soil backfilling is not impeded (Millet and Perez, 1981).

Filtrate loss for a bentonite slurry is determined by a standard filter press test (American Petroleum Institute (API) Test RP13B). The filter press test is used to simulate the formation of filter cake that is built up on the excavated surfaces by the electrokinetic and seepage forces pushing the slurry through the sides of the trench. Filtrate loss and corresponding

cake thickness are indicative of how much slurry loss will occur
during excavation of the trench, and how fast the cake will form
or reform on the sides of the trench if damaged, e.g., by the
excavating tool. A normal range of filtrate loss for bentonite
slurries for slurry wall construction is from 25 to 30 cubic
centimeters (Millet and Perez, 1981).

The last important control item on slurry properties is pH,
especially in an area where the chemistry of the soil excavated
or of the groundwater could dramatically change the pH of the
bentonite slurry mixture. The most desirable range for the slur-
ry pH is on the order of 6.5 to 10 (Millet and Perez, 1981).

Mixing of slurry is accomplished in either batch mixing op-
erations using high speed mixers in a tank that contains water
and bentonite, or continuous processing using flash or venturi
mixers. Mixing is continued until the desired Marsh funnel vis-
cosity reading is stabilized. After mixing and hydration of the
slurry, it is often placed in a pond for storage (see Figure
33). The slurry is then pumped to the active excavation area.

6.3.3.2 Trench excavation. The trench excavation design
should specify the minimum width and depth. In addition, it is
normal to specify a maximum deviation from plumbness for the
wall. With respect to depth and width, these criteria are usu-
ally established by the structural requirements of the wall,
the excavating equipment thought most appropriate for the site
conditions, and the depth and type of geological formations.

In setting the minimum thickness of the cutoff wall, the
hydrostatic head and permeability of the backfill materials
must be evaluated. Typically, a soil/bentonite backfill slurry
wall should have a thickness of 5 to 7.5 feet (1.5 to 2.3
meters). For a cement/bentonite slurry trench cutoff wall, the
increased shear strength of the backfilled wall has typically
permitted the wall thickness to be set at a minimum physical
excavation thickness, i.e., somewhere between 24 and 36 inches
(610 and 910 millimeters) (Millet and Perez, 1981).

The state-of-the-art of plumbness is such that walls have
been built to depths of over 400 feet (122 meters) with less
than a 6 inch (152 millimeter) deviation from the vertical,
i.e., 1:800. However, such severe limitations on verticality
should be specified only in cases where this is deemed to be a
necessary requirement for the intended purpose of the wall. On
most projects, tolerances of 1:80 to 1:100 have been used and
found to be satisfactory (Millet & Perez 1981).
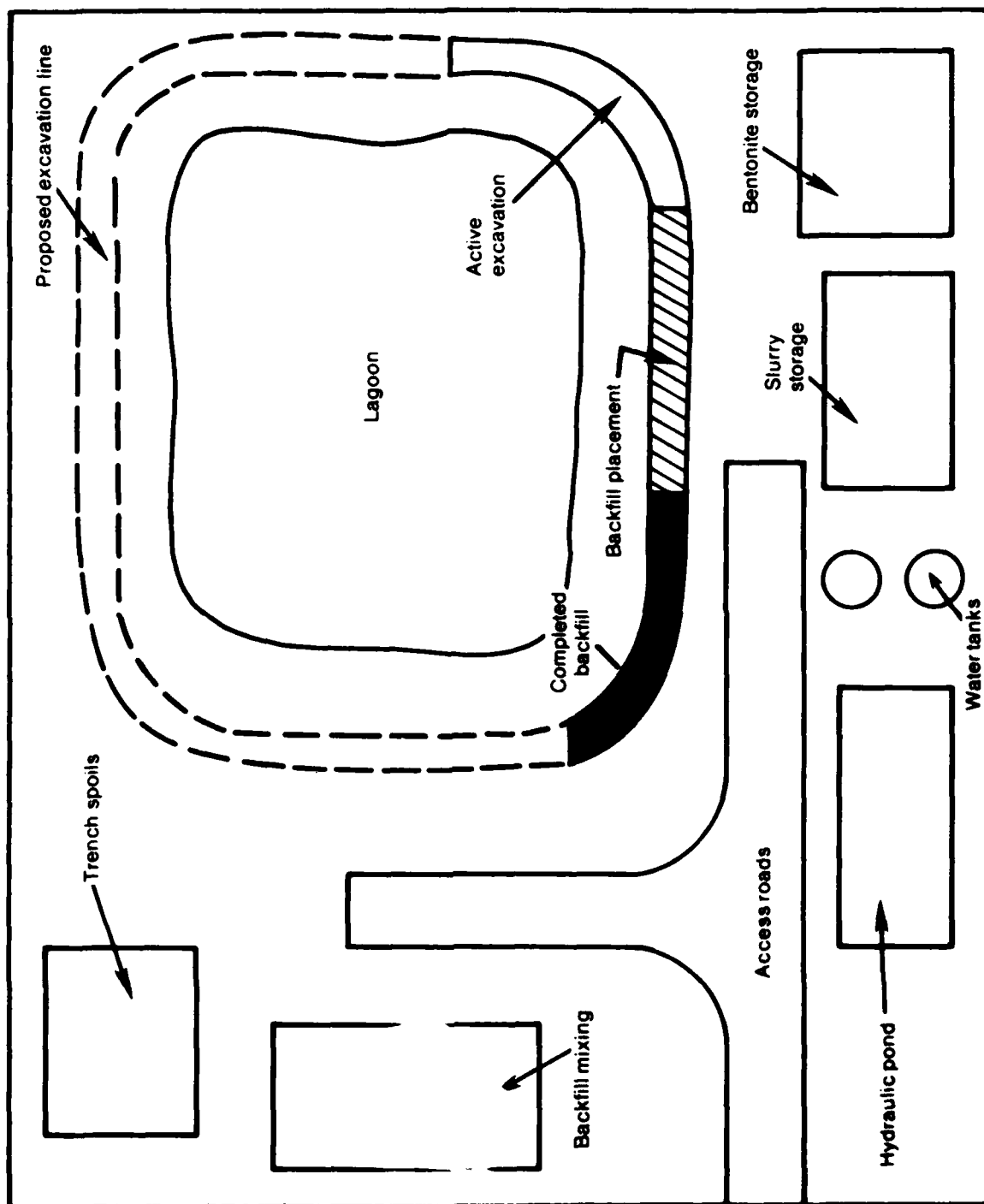
Figure 33. Typical slurry wall construction site.

6.3.3.3 Soil/bentonite backfilling. A schematic cross-section of a completed soil/bentonite slurry trench is shown on Figure 34. The bentonite slurry that penetrates the ground and the bentonite filter cake that is deposited on the walls of the trench during excavation contribute to the effectiveness of the cutoff wall.

The permeability of a soil/bentonite backfill material is dependent on both the soil gradation and the quantity of bentonite used in blending. Both factors are important. Figure 35 illustrates the relationship between soil/bentonite backfill permeability and the quantity of bentonite in the blend for several different types of soil. The amount of bentonite normally added to the soil bentonite backfill by way of the slurry used to sluice the soil during blending is 0.5 to 1.5 percent, depending on the initial water content of the soil. Therefore, if higher bentonite contents are required, dry bentonite must be added to the mix. Figure 35 demonstrates that low permeability can be achieved either by adding large amounts of bentonite to relatively coarse-grained or poorly graded soils (silts, sands, and gravels) or by utilizing significant amounts of clay soil in the blend and relatively small amounts of bentonite.

6.3.3.4 Slurry wall connections. In the instances where slurry trench cutoff walls have failed to perform to design expectations, experience has shown that the failures have been due either to an imperfect connection between the slurry trench cutoff and the underlying aquiclude (e.g., clay layer or competent, tight bedrock), or failure to completely excavate the slurry trench, thereby leaving zones of unexcavated pervious material above the aquiclude. When keying a cutoff trench into an underlying clay layer, a minimum key depth of at least 2 to 3 feet is normally used to achieve an adequate connection. As shown in Figure 36, the key must be deep enough to penetrate any pervious lenses, weathered zones, dessication cracks or other geological features that might permit seepage under the cutoff (D'Appolonia, 1980).

An effective connection between a cutoff trench and bedrock is often a difficult proposition. The key must obviously be sufficient to penetrate broken zones and the weathered rock surface. Sometimes these materials can be excavated with trench-digging equipment. However, excavation into rock, even if the rock is jointed and fractured, is often impossible except by using percussion tools or other equipment that further fractures and breaks the rock. In many cases, it is more appropriate to grout the contact between the slurry trench cutoff and the rock (Figure 36) than attempting to advance the cutoff into rock. (D'Appolonia, 1980).
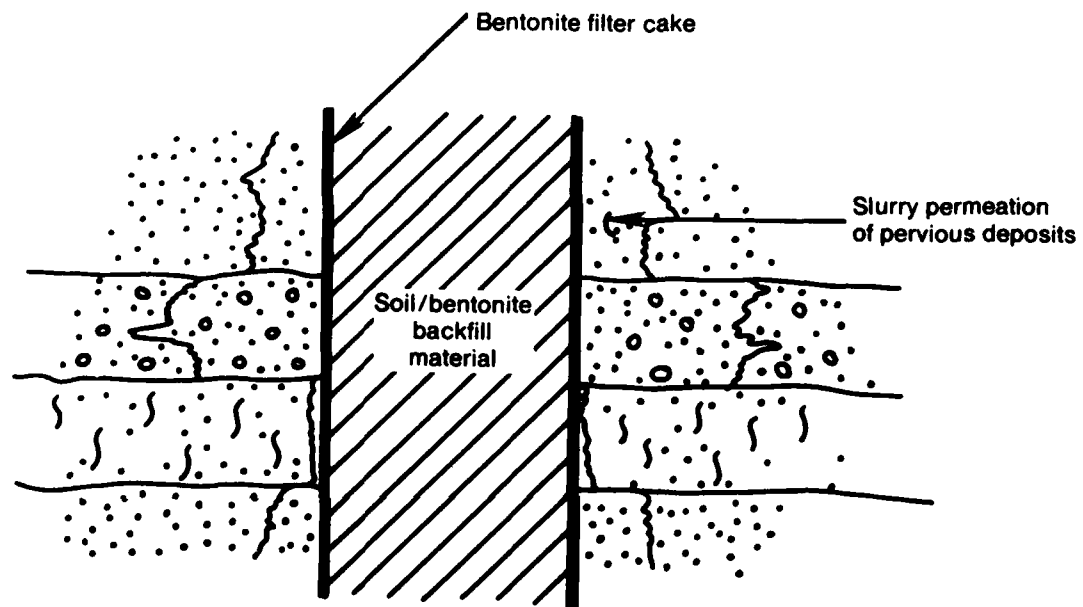
Source: D'Appolonia, 1980 (reproduced by permission of the author)

Figure 34. Schematic cross-section of slurry trench cut off.
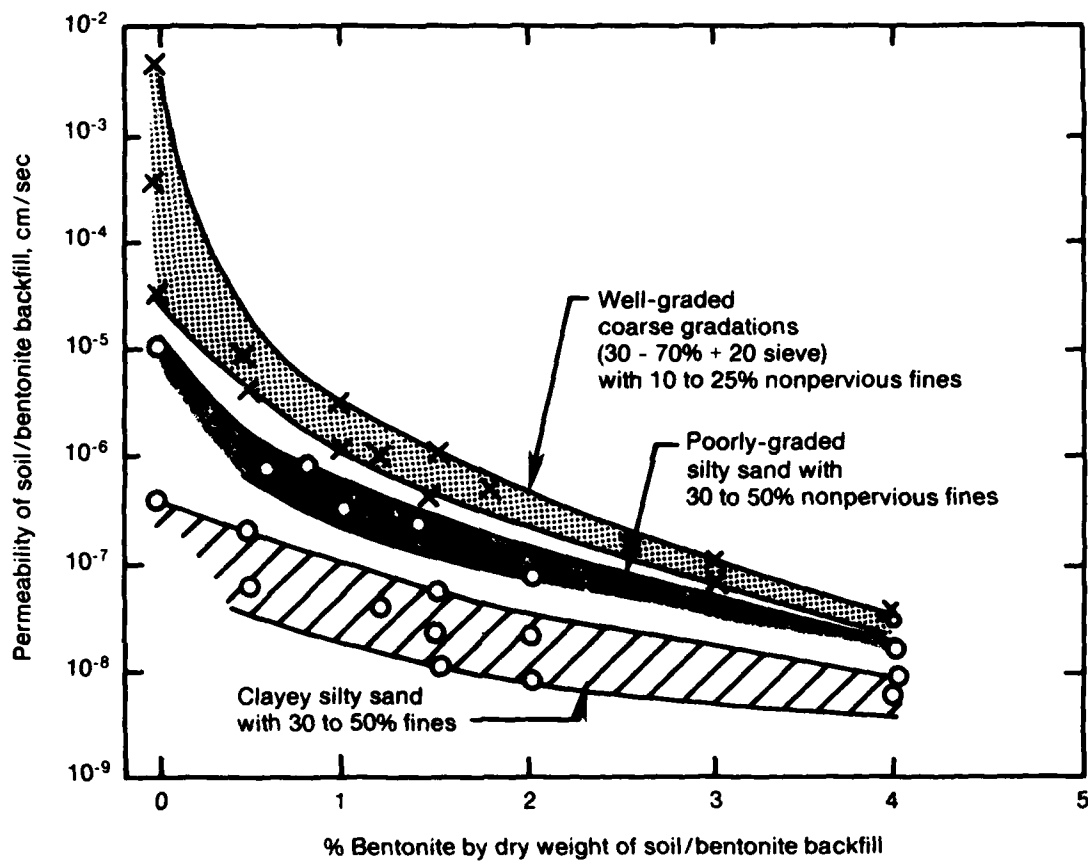
Figure 35. Relationship between permeability and quantity of bentonite added to soil/bentonite backfill.

Source: D'Appolonia, 1980 (reproduced by permission of the author)

Ground surface

Pervious soil

Pervious
lense

2 feet minimum

Clay layer
aquiclude

Ground surface

Pervious soil

Loose weathered rock

Grout after slurry
wall construction
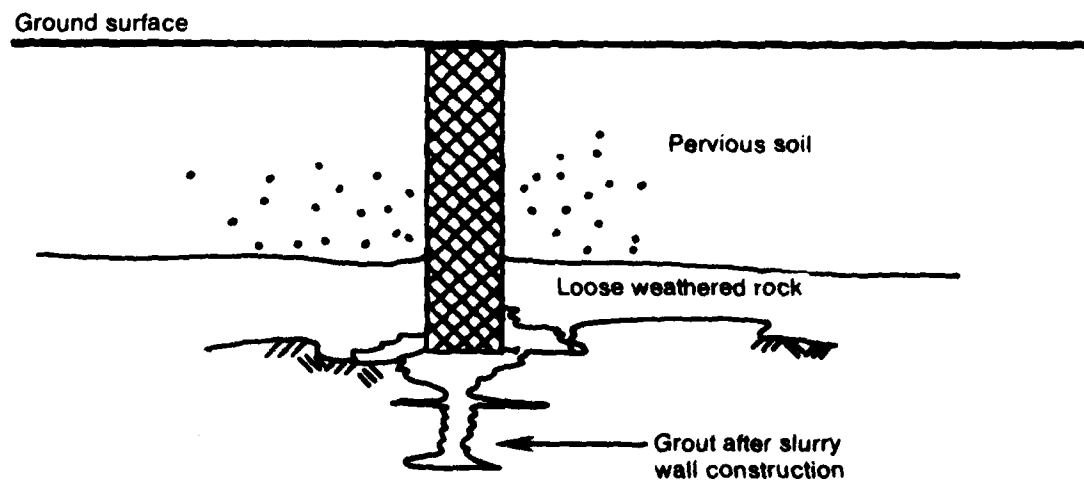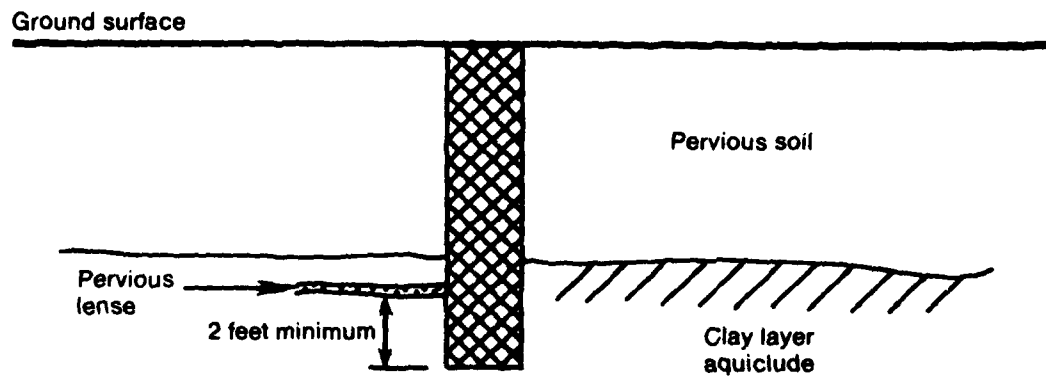
Source: D'Appolonia, 1981 (Courtesy of Dino D'Appolonia, President ECI)

Figure 36. Slurry trench bottom keys.

Sometimes slurry trench cutoffs are used in connection with dikes constructed above grade. Depending on available dike construction materials, the economical procedure may be to first construct the dike and then construct the slurry trench cutoff through both the dike and the foundation as shown on Figure 37. When impervious dike construction materials are available, it is usually more economical to construct the slurry trench through the foundation and then construct the impervious dike over the slurry wall. In this latter case, the connection between the slurry trench and dike is an extremely important detail (D'Appolonia, 1980).

6.3.3.5 Economic considerations. The cost of a slurry wall varies greatly depending on the following factors:

(a) Type of geological formation.
(b) Depth of excavation and type of equipment.
(c) Size and perimeter of lagoon.
(d) Source and availability of bentonite and backfill material.
(e) Site topography and accessibility.
(f) Environmental constraints.

The unit cost (per square foot) of slurry wall is most sensitive to the following:

(a) Depth of trench.
(b) Type of geological material.
(c) Type of backfill material.

The following ranges are based on recent cost estimates:

(a) Soil/bentonite slurry wall excavated in soft to medium soils:

- Up to 30 foot depth $3 to 6/square foot
- 30 to 50 feet $7 to 10/square foot
- 75 to 125 feet $8 to 15/square foot

(b) For hard soils the cost per unit area increases by a factor of 2 over soft soils ($6 to $30/square foot, depending on depth).

Waste material

Pervious materials

Dike

Aquiclude

2 feet minimum

Slurry trench

10 feet minimum

3
4
1
2

Waste material

Pervious materials

Aquiclude

Impervious
material

1 Compacted clay blanket
2 Slurry trench
3 Wet-plastic transition material
4 Impervious core

1 Compacted clay blanket
2 Slurry trench
3 Wet-plastic transition material
4 Impervious core
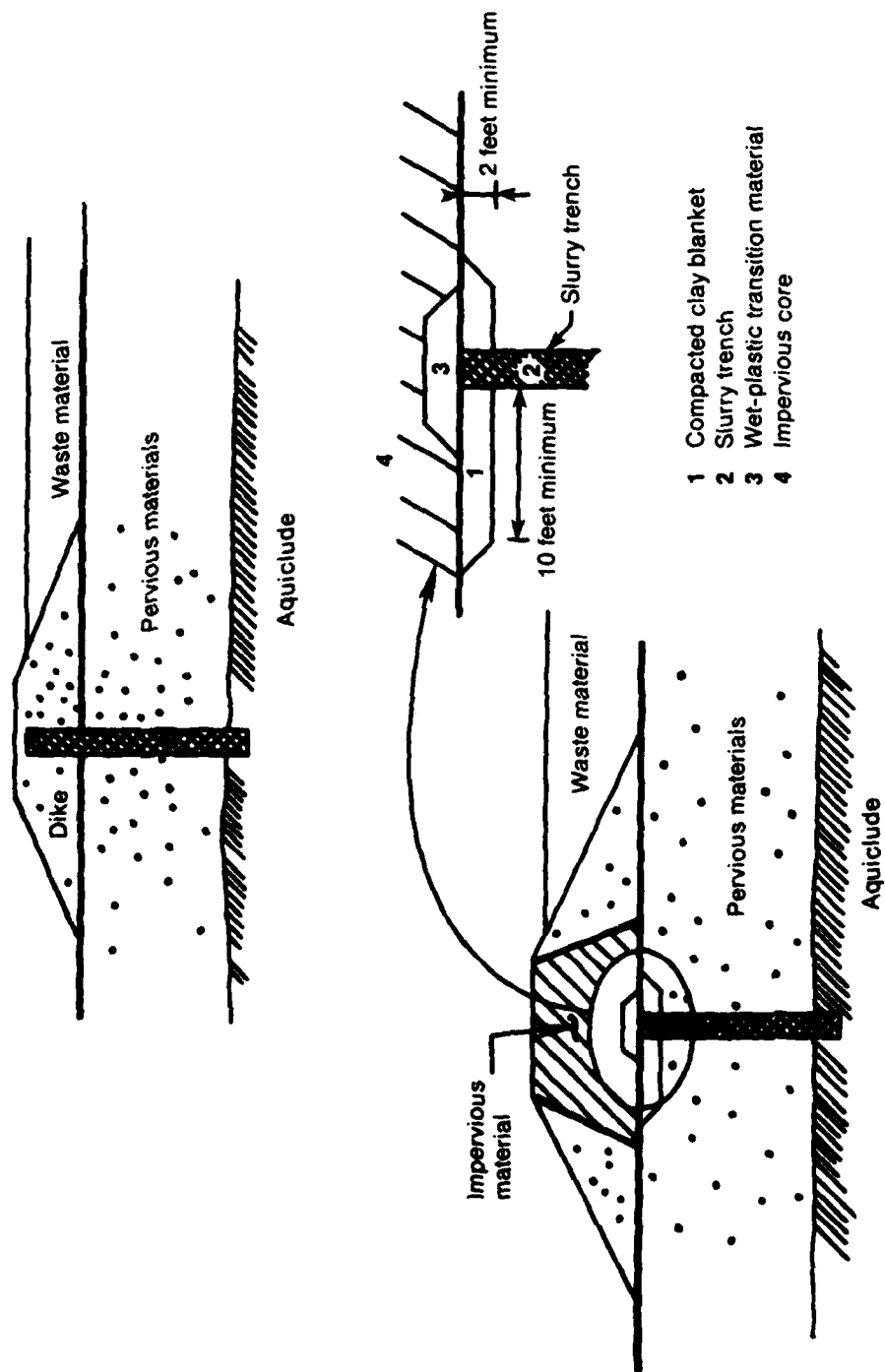
Figure 37. Slurry trench connections for dike construction

(c) When excavating in soft to medium rock, sandstone, or shale the cost per unit area ($10 to $60/square foot) is usually three to five times the unit cost for slurry walls constructed in soft soil ($3 to $6/ square foot).

(d) Backfilling with cement/bentonite versus soil/bentonite, increases the unit cost by a factor of four (i.e., $20 to $200/square foot, depending on the depth of excavation and the type of geological materials).

6.3.4 Construction verification. The critical issue in application of a slurry wall as a device for pollution abatement is its ability to prevent or greatly reduce the potential of contaminant migration from the waste disposal area. An effective slurry wall must, therefore, meet all the engineering performance requirements, as well as a set of environmental performance requirements including permeability and compatibility with contaminants. The following subsections address the means of short and long-term testing quality control and verification of performance, respectively.

In addition to the contractor's quality control, geotechnical organization is often used for construction quality assurance. Such geotechnical quality assurance services may include spot testing of the appropriate specified criteria, i.e., slurry viscosity, slurry density, slump of backfill, depth of trench bottom, etc. The frequency of the spot checks and spot testing would be dependent on the volume and production of work and the discrepancy, if any, between spot checks and the contractor's quality control testing (Miller and Perez, 1981). The following paragraphs describe some of the key test procedures required for QC/QA.

6.3.4.1 Materials quality control. A rigorous quality control program should be maintained through all construction steps of the slurry wall. This usually covers water quality, bentonite type, slurry quality, backfill characteristics, etc. Table 26 lists key parameters of the material quality control program for bentonite slurry walls (Federal Bentonite, 1981).

6.3.4.2 Filtrate loss test. One of the key tests that should be conducted prior to placement of slurry in a trench is filtrate loss. This test simulates the formation of filter cake on the inner walls of the trench. This test involves measuring the amount of water lost from a 25-cp slurry through filter paper when subjected to a pressure of 100 psi for 30 minutes

TABLE 26. MATERIALS QUALITY CONTROL PROGRAM FOR BENTONITE SLURRY WALLS

Subject	Standard	Type of test	Frequency	Specified values
Water	---	-pH -Total hardness	Per water source or as changes occur	As required to properly hydrate bentonite with approved additives
Additives	---	Manufacturer certificate of compliance with stated characteristics		As approved by engineer
Materials — Bentonite	SPI Standard 13A	Manufacturer certificate of compliance		Premium grade sodium cation montmorillonite
Backfill soils	---	Selected soils obtained from a borrow area approved by the engineer Roll to 1/8" thread		65 to 100% 3/8" sieve 35 to 85% passing #20 sieve 15 to 35% passing #200 sieve
Slurry — Prepared for placement in the trench	API Standard 13B	-Unit weight -Viscosity - Filtrate loss	1 set per shift or per batch (pond)	Unit weight 1.03 gm/cc/ V - 15 centipose of - 40 sec-March at 68° Loss - 15 cc in 30 min at 100 psi
In trench	API Standard 13B1	-pH -Unit weight	1 set per shift at point of trenching	pH 8 Unit weight = 1.03 - 1.36 gm/cc
Backfill mix — At trench	ASTM C 143	-Slump -Gradation	1 set per 200 cu yds	Sump 2 to 6 inches 65 to 100% passing 2/8" sieve 35 to 85% passing #20 sieve 15 to 35% passing #200 sieve

Source: Federal Bentonite 1981.

(Grim and Guven, 1978). A test tnat is often specified tor fil-
trate loss is the American Petroleum Institute (API) Recommended
Practice) "Standard Procedure for Testing Drilling Fluids," API
RP 13B (API, 1982).

6.3.4.3 Slurry viscosity. Marsh cone readings, which are
used to measure slurry viscosity, measure a series of interre-
lated properties including density, viscosity, and shear
strength (Hutchison et al., 1975). These tests indicate the re-
sponse of the slurry to conditions found in the trench. For ex-
ample, Marsh cone readings less than 40 seconds indicate a slur-
ry that has poor filter cake formation and insufficient trench
supporting ability. Marsh cone readings also indicate the work-
ability of the slurry. If the reading is too high, the slurry
can become too dense and difficult to work with. If it is too
low, trench wall stability may suffer (Ryan, 1976).

D'Appolonia (1980) found that slurry viscosity has a direct
influence on filter cake permeability and is one of the most
crucial slurry characteristics. The relationship between vis-
cosity and filter cake permeability is shown on Figure 38.

6.3.4.4 Slurry density. The density of the slurry should
be tested to ensure tnat the slurry in the trench is slightly
heavier than groundwater. The specified maximum unit weight
typically ranges from 65 to 75 pounds/cubic foot (29 to 34 kilo-
gram/cubic meter).

6.3.4.5 Excavation tolerance. Field quality control pro-
cedures must be followed to ensure that minimum width and depth
of the wall have to be accomplished. In addition, the plumbness
ot the wall itself must be verified. For most projects, toler-
ances of plumbness are specified to not exceed 1:100 (Millet and
Perez 1981).

6.3.4.6 Backfill material. Quality control of backfill
material should demonstrate that the material has the following
characteristics:

(a)   Is free of incompatible materials such as organic mat-
      ter, debris, salts, gypsum, etc.
(b)   Has suitable particle size distribution.
(c)   Mixes with slurry to form a homogeneous paste.
(d)   Contains the specified fraction of bentonite.
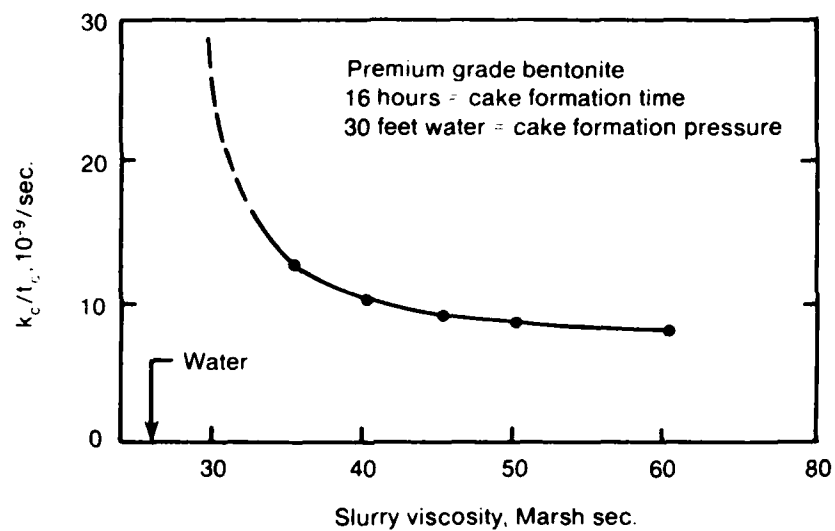
Source: D'Appolonia, 1980 (reproduced by permission of the author)

Figure 38. Relationship between cake permeability
and slurry viscosity.

The slump of the backfill material is an expression of it tendency to flow. This test gives a practical measure of back till material performance in the slurry trench. An optimu range of slump that is specified for backfill material range from 2 to 7 inches (Case, 1982). The density of the backfil material should also be tested in the field and kept within a optimum range of 105 to 120 pounds/cubic foot (1,680 to 1,92 kilograms/cubic meter). At such conditions ,the backfill mate rials easily displaces the slurry in the trench forming succes sive layers of low permeability materials, as shown on Figure 3 (D'Appolonia, 1980).

The sheer strength of the backfill must be high enough t allow it to stand on a 5:1 to 10:1 slope (Millet and Perez 1981). Additional geotechnical properties of backfill materia include testing for resistance, hydraulic pressure, plastic de formation potential, and consolidation properties to ensure lon term-integrity of the slurry wall.

6.3.4.7 Permeability. Permeability is a key element in th performance of the slurry wall and is a function of several fac tors including bentonite content in slurry and backfill, grai size distribution, density, and chemical contaminants in ground water. A field and laboratory program to test permeability mus be an integral part of the construction quality control of th slurry wall (e.g., ASTM standard test method for permeabilit of granular soils, ASTM-D2434, 1982). The results of the permea bility of a slurry wall range from 1×10^{-6} to $1 \times 10^-$ centimeters/second. A common goal is, however, 1×10^{-7} cen timeters/second.

6.3.4.8 Connection with aquiclude. Adequate keying (con nection) in the aquiclude should be 2 feet at a minimum (D'Ap polonia, 1981). Construction quality control should include means of measuring and verification of excavation depth and pen etration of the aquiclude. Observations should also demonstrat that the trench bottom is tree of boulders or trench wall mate rial that may have collapsed during construction. Use of drill ing techniques as a positive means of verification is common Geophysical techniques may also be utilized as confirmatory ap proaches.

Station
reference to distance
(hundreds of feet)

8 + 00   10 + 00   12 + 00   14 + 00   16 + 00   18 + 00
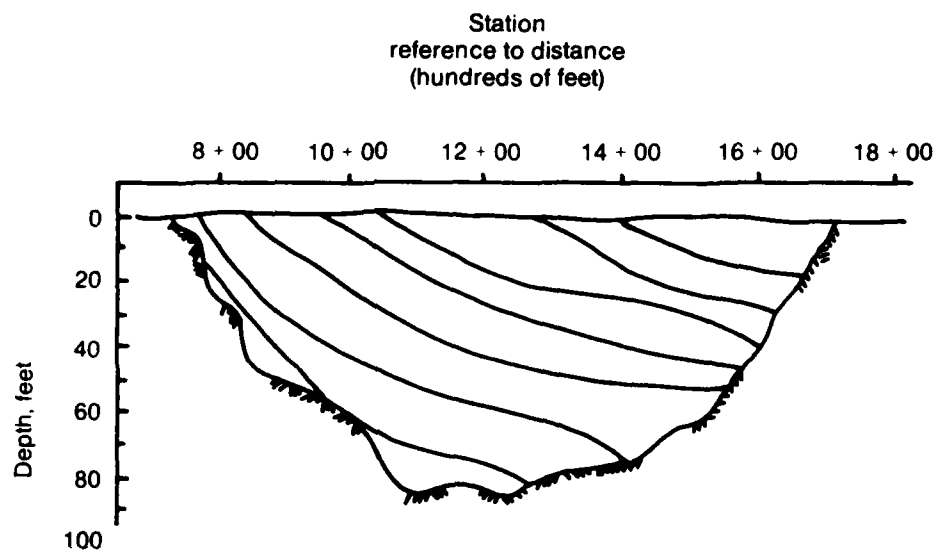
Figure 39. Typical backfill profile in trench with irregular bottom.

6.3.5 Environmental performance verification. The previous subsection discussed key elements of technical considerations and quality control that are necessary for effective design and placement of slurry walls as a means of in-place closure of inactive lagoons or other land disposal sites. It should be emphasized that environmental performance could be achieved only if proper technical factors and quality control are implemented in every step of design and construction including waste characterization, site characterization, materials testing, slurry testing, trench measurements, backfill material testing, and verification of slurry wall connection with the designated aquiclude.

The main concern in application of slurry walls as a pollution abatement technique is the long-term stability and longevity including chemical attack on bentonite and the consequent loss of resistance to flow and ground instability. Table 27 lists potentials related to slurry wall effectiveness and possible associated monitoring methods (Dunicliff, 1980). The following subsections briefly outline such monitoring and performance verification methods.

6.3.5.1 Basal stability. Basal stability could be measured by an inclinometer, which is an instrument that measures the subsurface horizontal movement either of the slurry wall itself or the ground behind the wall. The inclinometer system consists of a pipe installed in a bore hole with internal guide groves. A torpedo containing an electrical tilt sensor is lowered into the pipe and is connected by an electrical cable to a device calibrated to read the tilt of the torpedo relative to the vertical. The changes in alignment of the pipe provide the data necessary to calculate horizontal movement of the wall or the ground (Dunnicliff, 1980).

6.3.5.2 Ground movement. In addition to the inclinometer system, horizontal ground movement can be measured by means of optical surveys using a steel tape or scale at right angles across a line of sight between a fixed transit position and a permanent foresight. The accuracy of this method is normally +0.01 foot. Multipoint extensometers installed horizontally or slightly inclined downward through bore holes in the slurry wall, could be used to measure the relative movement between the end of each rod and the head that relates to the horizontal movement (Dunnicliff, 1980).

TABLE 27. POTENTIAL PROBLEMS RELATED TO SLURRY WALL EFFECTIVENESS AND POSSIBLE ASSOCIATED MONITORING METHODS

Potential problem	Parameters	Possible measurement/ monitoring Method
Basal instability	Horizontal movement of ground	● Inclinometer
Ground movement behind wall	Horizontal movement of ground	● Optical survey ● Inclinometer ● Horizontally installed ● Piezometer
	Multipoint extensometers	
	Vertical movement of ground	● Optical survey ● Subsurface settlement gauge
Groundwater level	Groundwater level	● Observation well
	Pore pressure	● Piezometer
	Chemistry	● Sampling wells
Surface water	Chemistry	● Direct sampling

Source: Dunnicliff, 1980

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6.3.5.3 Subsurface settlement. Settlement can be measured by single point or multipoint gauges. The former consists of a steel anchor that is mechanically set at the bottom of a bore hole. The anchor is connected to a riser that is optically surveyed on the top of the pipe to determine the degree of settlement. A multipoint gauge consists of a corrugated plastic pipe installed in a vertical bore hole with stainless steel wire rings installed around the pipe at regular intervals. Grouting material is placed in the space between the pipe and the bore-hole wall. A probe attached to the end of an electrical cable and survey tape is used to measure the distance between the steel wire rings. This information is then used to compute values of vertical settlement (Dunnicliff, 1980).

6.3.5.4 Groundwater levels. Groundwater Levels can be used to determine the relative hydraulic head drop across the wall and, thus its effectiveness in isolating the site. Monitoring wells and/or piezometers are installed at both sides of the wall to collect groundwater elevation data which could be utilized in determining groundwater flow pattern through the wall.

6.3.5.5 Groundwater quality. Groundwater quality information for wells at both sides of the slurry wall can also be used to establish the effectiveness of the wall in containing or attenuating the contaminants.

6.4 Grouting techniques.

6.4.1 Process description. Grouting is a process by which
a fluid of thixotrophic material is injected into earth material
to penetrate and gel or set in place. This results in a lower
permeability of the grouted area as compared to the adjoining
earth material. These techniques have been used for many years
in the geotechnical field to aid in dam and tunnel construction.

Generally, grouting material can be classified in the fol-
lowing manner:

(a) Suspension grouts which contain fine colloidal materi-
     als such as bentonite, portland cement, or a mixture
     of both in a suspension of water.
(b) Chemical grouts that consist of Newtonian fluids such
     as silicate-base material, organic polymers, bitu-
     mens, etc.

Suspension grouts have been used predominantly in U.S. ap-
plications, while chemical grouting has been the dominant appli-
cation in Europe (U.S. EPA, 1982). Suspension grouts are gener-
ally more viscous with larger particle size and are best used in
grouting rock or coarse material. Chemical grouts initially have
lower viscosities and may be used for finer grained, cohesion-
less soils.

Pressure injection of grout material is as much an art as a
science; it involves drilling holes or driving vibrating beams
into the earth material to be sealed, and injection of grout
using specialized equipment. An example of a grout curtain is
shown on Figure 40 (U.S. EPA, 1978).

Application of injection grouting as a means of isolation of
lagoon contents or contaminants in groundwater is very limited
due to the following reasons:

(a) Injection grout curtain construction is usually three
     times as costly as conventional slurry wall isolation
     techniques (U.S. EPA, 1982).
(b) Potential limitations of bentonite slurry walls (e.g.,
     chemical compatibility, connections etc.) will limit
     the application of grout curtains as a means of in-
     place lagoon closure as well. Clay or bentonite
     grouts will exhibit the same potential compatibility
     problems as discussed for slurry walls.

Waste material

Semicircular grout curtain

Grout tubes

Depth below grade

Length
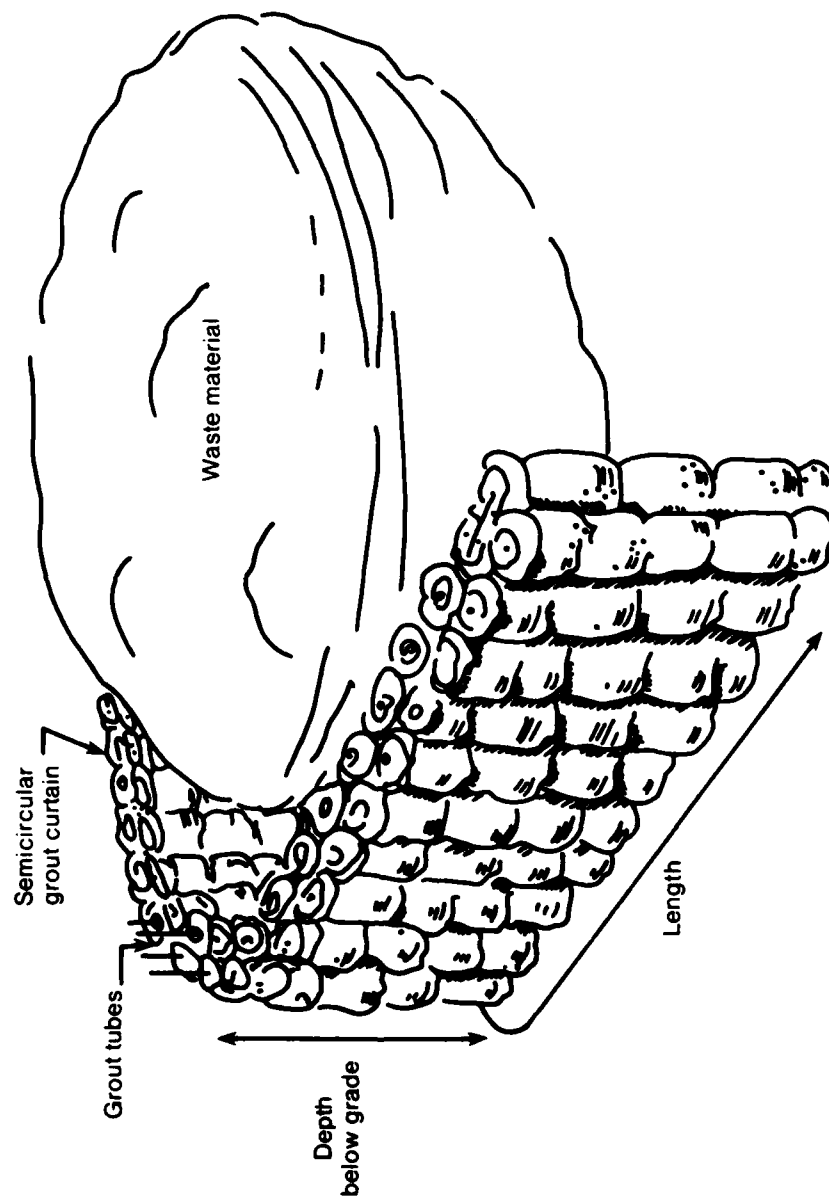
Source: EPA, 1978

Figure 40. Semicircular grout curtain around upgradient end of a waste area.

(c) It is extremely difficult to ensure continuity, integrity, and to verify performance of grout media after injection in the ground. Injection grouting may be, however, of benefit in sealing localized void areas of porous fractured rock where other methods of groundwater control are not applicable (U.S. EPA, 1982).

Grouting techniques as a means of waste isolation could be in the form of the following:

(a) An upgradient curtain to divert groundwater flow away from waste as shown in Figure 41.
(b) Complete encirclement of the lagoon area or contaminated area for groundwater diversions, or total containment of the waste or leachate plume.
(c) Downgradient containment from the disposal area to intercept contaminated groundwater and allow recovery of contaminants.

It should be noted, however, that downgradient containment may face greater chemical compatibility problems with leachate and contaminated groundwater (U.S. EPA, 1982). Moreover, downgradient containment grouting would work only if a set of wells is inserted between the barriers and the lagoon to recover contaminants from groundwater.

6.4.2 Process design methodology. The design of grouting systems must consider these basic components:

(a) Grouting materials and how they can be applied.
(b) Construction techniques.

6.4.2.1 Grouting materials. A wide range of grouting materials is commercially available for various geotechnical applications. The following paragraphs contain descriptions of some of the common materials used.

Clay grouts -- Clay grouts are mostly sodium (montmorillonite) material that is capable of swelling up to 12 times its original volume when wet. Sodium montmorillonite is more commonly known as Wyoming bentonite. Because of its higher viscosity, swelling properties, and lower cost as compared to other grouting material, bentonite has been used to fill voids in coarse
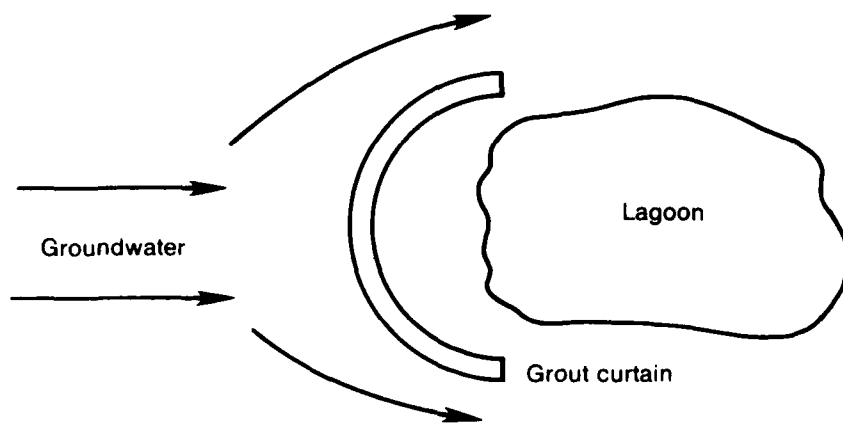
a. Upgradient diversion
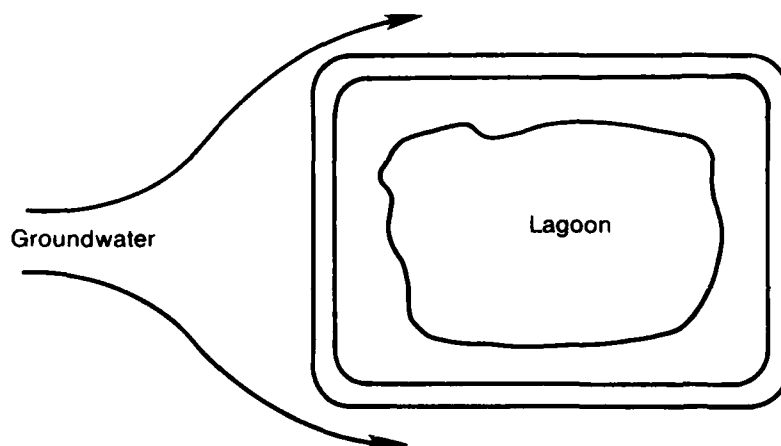
b. Encirclement
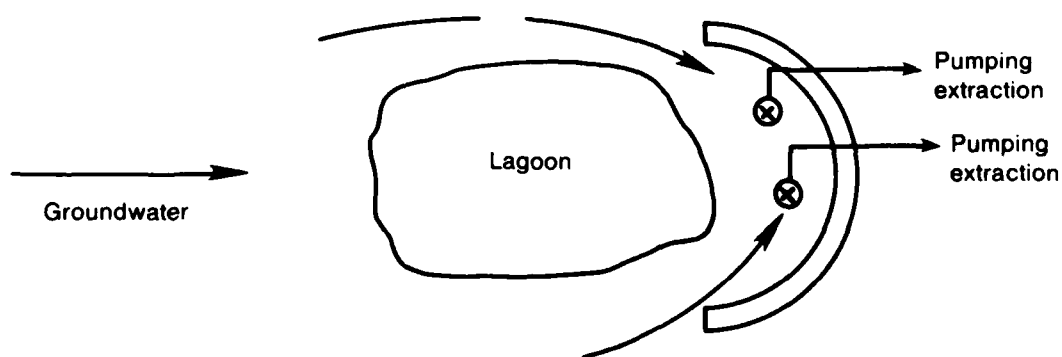
c. Downgradient interception

Figure 41. Grout curtain configuration.

sands and gravel. The performance of clay grout material is affected by various factors, including the following:

(a) The texture of the soil being grouted. Because of its slow set time and low strength, grout material can be washed out from highly permeable soil (in excess of 10^{-1} centimeters/second) or coarse-textured soil material such as open gravel. This washout can occur right after injection if it is subject to water gradients in excess of three units (Greenwood and Ruffle, 1963).

(b) Strong organic and inorganic acids and bases can dissolve or greatly alter clay material and drastically increase permeability (D'Appolonia, 1980).

(c) Many inorganic compounds and salts could produce shrinkage of clay particles and thus increase permeability (D'Appolonia, 1980).

(d) Some organic compounds could be adsorbed onto clay surfaces, and may, therefore, affect the water layer spacing and permeability of grouted material (Anderson, Brown and Green, 1982).

A more detailed discussion of chemical compatibility of bentonite clay with various waste materials has been presented in subsection 6.3.

Cement grouts -- Cement grouts utilize hydraulic cements that set, harden, and maintain integrity under water. Several types of cement have been used for grouting. These include the following:

(a) Type 1 (ordinary portland cement).

(b) Type 2 (modified portland cement, moderate sulfate resistence).

(c) Type 5 (low alumina sulfate resistance cement).

Various fillers such as clay, sand, and pozzolanic material (such as fly ash) may be used to enhance characteristics and grout resistance to chemicals (Bowen, 1981).

Cement grouting has been used effectively in various field applications. However, its effectiveness for in-place lagoon closure may be limited because of the vulnerability of cements to chemical attack from various chemical constituents, including strong acids, strong bases, sulfates, and organic acids as shown in Table 28.

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TABLE 28. MATERIALS INCOMPATIBLE WITH CEMENT GROUT

Type of cement	Compound
Cement mortar (portland, portland/ slag)	Sulfates (Na, K, Ca, Mg) Dilute H_2SO_4 (pH 4-7) Other dilute acids/acid salts (pH 4-7)
Cement mortar (calcium aluminate)	KOH, NaOH Other dilute acids/acid salts (pH 4-7)* Hypochlorite (Na, Ca)[a]
Soil cements	Organic soils (>1-2 percent organic material) Sulfates Excess salt HNO_3 Highly ionic materials Strong acids Strong bases
Concrete	Animal oils Polyhydroxy organic compounds Salt solutions Mild acids Oxidizing acids Sulfates (Mg, Na, ammonium) Organic acids Halides Organic solvents and oil Organic materials Metal salts (Mn, Cu, Pb, Sb, Zn) Mineral acids
High alumina cement	Strong alkali

[a]Questionable

Source: ASTM, 1982; Ingles and Metcalf, 1973; Matrecon, Inc., 1980; Haxo, 1980 Fung, 1980; Tomlinson, 1980; Malone, Jones, and Larson, 1980; Thompson, Malone, and Jones, 1980; ACI Committee 515, 1979.

Cement/bentonite grout -- Cement/bentonite grout has better strength than clay grout alone and, thus, could resist washout under greater hydraulic gradients. The mixture, however, has higher permeability than clay only grouts. The compatibility of cement bentonite grout is the resulting resistance and compatibility of the cement and the bentonite together.

Bitumen grouts -- Bitumen grouts consist of asphaltic emulsions of bitumen, water, soap, kacine, and other fillers such as clay. After injection of the bitumen grout mixture in the ground, the emulsion starts breaking up on contact with soil (due to adsorption of emulsifers or addition of destabilizing agents). The more viscous compounds (e.g., bitumen) will fill the voids or fissures of the soil and result in grouting. Bitumen alone is a highly viscous material. However, after it is emulsified with water a low viscosity emulsion is produced.

Oxidation and aqueous leaching of oxidation products are the main causes of bitumen degradation. Bitumen is not compatible with mineral acids, most polar and nonpolar solvents, and chlorinated, aliphatic, and aromatic hydrocarbons. Wastes that are highly ionic, have a high salt content, and strong acids and strong bases are also not compatible with asphaltic mixtures (Haxo, 1980).

Bitumen grouts are generally not suitable for use in coarse material or sealing large fractures; it is more suitable for fine sands and finer soils. Bitumen is known to have long-term stability under normal environmental conditions (Tall and Canon, 1977).

Silicate grouts -- Silicate grout consists of alkali silicates, water, and gelling or setting agents. The grout may also include accelerators. Alkali silicates are the most widely used class of grouts in the chemical grout category. Sodium silicate is typically used in the grout. Silicate grout is durable and maintains waterproofing characteristics for a long period of time (Talland and Caron, 1977). Long-term strength and impermeability, however, may deteriorate with time due to water expulsion, shrinkage, dessication, and solution erosion by groundwater (Hurley and Thornburn, 1971).

Sodium silicate grouts are more applicable to less permeable soils ($< 10^{-2}$ centimeters/second) and not generally suitable for sealing large fractures or more permeable soils.

Organic polymer grouts -- Organic polymer grouts consist of organic chemicals (monomers) that polymerize and cross link to form insoluble gels such as acrylanide, phenolics, urethane, urea formaldehyde, epoxy, and polyester material. These grouts may be used alone or with other grouts such as silicates, bitumens, clay, or cement (Talland and Caron, 1977). Many of the materials, however, are not suitable candidates at this time for in-place lagoon closure because of costs, toxicity of the grout material, need for specialized handling equipment, and incompatibility with waste-containing acids, bases, salts,, and organic materials.

6.4.2.2   Application of grouting methods.   In addition to the various grouting materials discussed in the previous section, several construction techniques are available for the application of grout. These techniques must be considered when developing the design of a grouting system for lagoon closure.

Curtain grouting -- Curtain grouting is used to form an impermeable vertical wall below the ground surface. This type of grouting will achieve similar results as that discussed for the slurry walls. Curtain grouting involves the placement of an impermeable barrier by means of injecting grout along a vertical profile. Two methods may be employed for curtain grouting:

(a)   Injection grouting using bore holes.
(b)   Vibrating beam injection.

Injection grouting using bore holes utilizes a layout of bore holes which are constructed through the soil column terminating in an aquiclude member. During or after the construction of the boreholes, grout is injected into the boring and allowed to permeate into the soil. Grout is injected at predetermined elevations in the bore hole so that the entire length of the soil column for each bore hole is grouted. Typically, a two-row grid pattern of bore holes is used in constructing the grout curtain as shown on Figure 42. This type of layout is designed to provide not only thickness but overlap of grout between bore holes so that a continuous seal is provided.
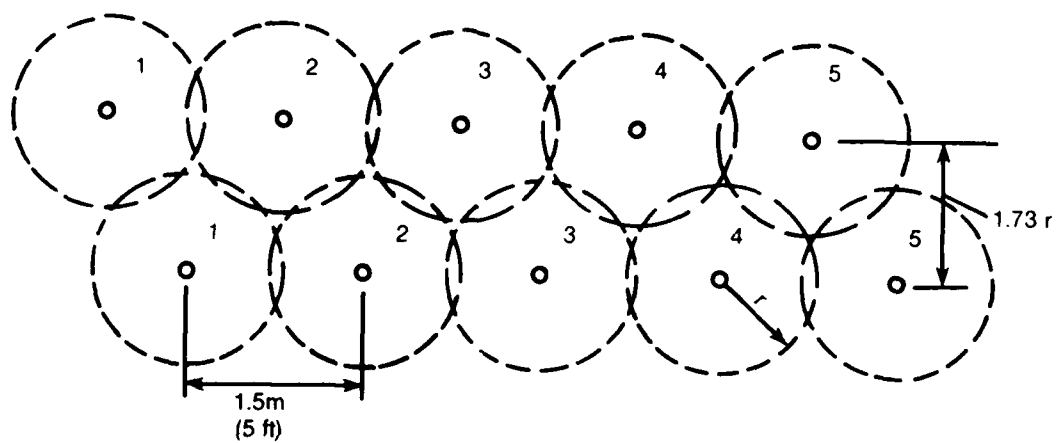
Source: EPA, 1978

Figure 42. Two-row grid pattern for grout curtain injection boring.

An alternative to this type of injection grouting
use of a vibrating beam for subsurface placement of the
along the soil column. This technique also results in
permeability subsurface wall that must tie into an aqu
member and its base. The vibrating beam utilizes a larg
beam that is driven into the soil to the specified depth
clude layer) using a vibrating hammer. The eye-beam i
slowly withdrawn and grout is pumped through a set of r
mounted on the leading edge of the eye-beam. As the b
withdrawn, the grout fills the cavity that is formed. Wh
beam is completely withdrawn, the cavity filled with gr
moved along the direction of the wall and process rep
Sufficient overlap must be provided between each segment
wall. Figure 43 depicts the vibrating beam method for
injection and also shows a typical 4- to 6-inch overlap b
beam-grouted sections.

Jet grouting -- Jet grouting is a technique that uses
pressure nozzle for placing grout in an opening or cavity
soil or soft rock. Using this approach, a cavity is formed
the jet nozzle and the cavity in turn filled with grout
the cavity has been formed using either water or grout
cutting fluid, which is injected by means of the nozzle
grout permeates the voids in the soil forming a low p
bility zone. By properly spacing the bore holes to be us
jet grouting, it is conceivable that a pattern could be de
whereby the jet grouted areas would overlap thereby for
wall or continuous impermeable layer. An alternate ap
would be to use the jet grouting technique for sealing loc
voids or permeable zones.

Area blanket grouting -- Area blanket grouting is a
nique that can be applied to form a grout blanket in s
soil layers. This grouting approach is based on low pr
injection of grout in permeable soils using shallow inj
holes. The location and the spacing of the holes is laid
that there is sufficient overlap of grout from each of tl
jection points so that a continuous blanket can be forme
primary application of this type of grouting may be to i
low permeability soil material for cover over a closed
area.
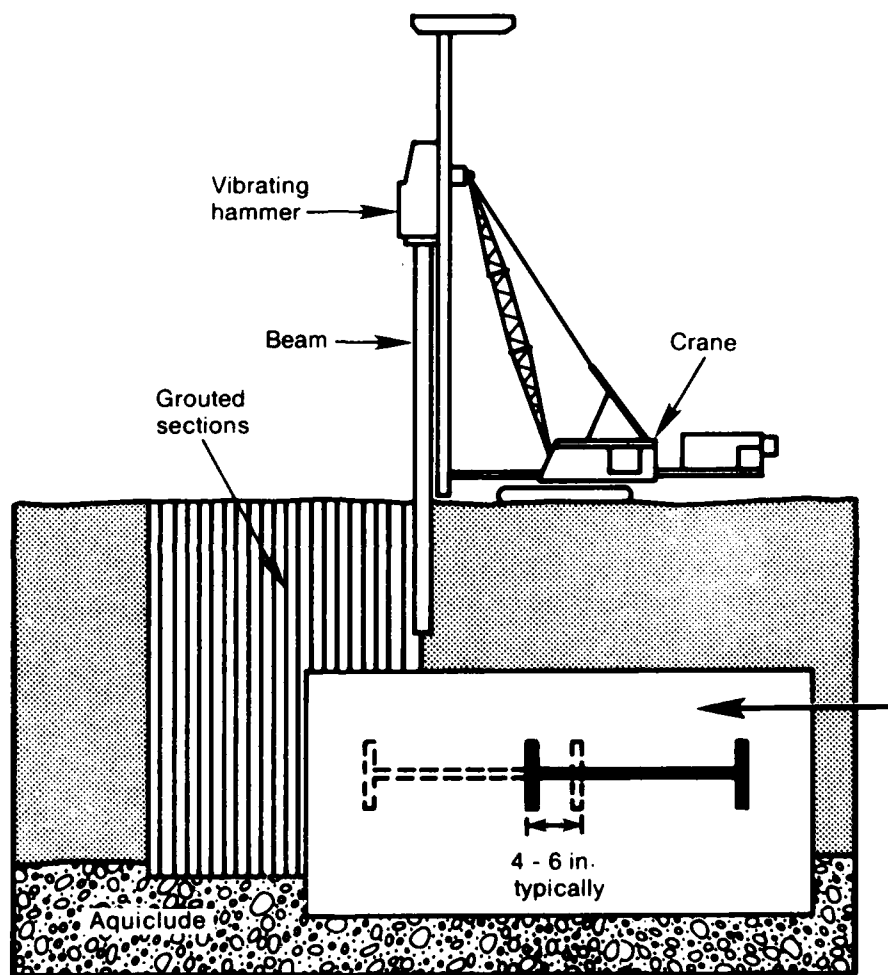
Figure 43. Vibrating beam techniques.

6.4.2.3 Bottom sealing methods. Grouting may offer an opportunity for bottom sealing of an existing lagoon. This type of application has received recent interest as a possible approach for constructing a "liner" under an existing lagoon without requiring excavation of the waste lining and then reburial of the waste. In essence, this could be viewed as an in-situ method for liner construction.

The bottom sealing approach utilizes a concept of injection grouting and jet grouting discussed in the previous sections. Two approaches may be considered for grout injection, as follows:

(a)   Directionally-controlled horizontal drilling under the lagoon followed by grout injection.
(b)   Vertical drilling through the waste and grout injection under the bottom of the lagoon.

Successive borings and grouting would be required in order to achieve a somewhat continuous layer. The spacing of the borings would be a critical design element so that sufficient overlap of the grouted sections would occur and a continuous impermeable layer formed.

Directional drilling has been used primarily in the oil drilling industry. Three basic approaches exist, as follows:

(a)   Directional drilling -- The drill penetrates the earth surface at an angle of 90° and then is intentionally deviated from the vertical by directional control of the drillhead.
(b)   Horizontal drilling -- A drill penetrates the earth surface at an angle less than 90°, but does not utilize any method for directional control of the drillhead.
(c)   Directionally-controlled horizontal drilling -- The drill penetrates the earth surface at an angle of less than 90° and directional control of the drill bit is also used to establish the drilling path.

The horizontal drilling approach may not be a viable method for bottom sealing because it cannot provide the level of accuracy in boring spacing and vertical control necessary to ensure that a continuous grout layer is constructed (Kitchens, 1980). The directional drilling technique may have only limited application for lagoon bottom sealing because of the relatively small

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rate of bend or curvature that can be achieved using this method. This would be particularly restrictive for application in shallow lagoons. The more promising of the three methods is the directionally controlled horizontal drilling approach. Figure 44 shows a schematic of the type of drill rig that may be used showing a 25° angle with the ground surface. Using this type of rig with a directionally controlled drill bit, it may be theoretically possible to bottom seal lagoons. Several problem areas must be identified, as follows:

(a) Grouting using suspension grouts would not be viable if the soils under the lagoon showed moderate to low permeability, i.e., less than 10^{-2} centimeters/second.

(b) Costs will be relatively high considering the specialized equipment and sophisticated controls.

(c) There is no method for ensuring or verifying that a continuous grout seal would be formed under the lagoon.

(d) There is a potential for fracturing or accidentally drilling through the bottom of the lagoon that may result in a release of contaminants from the lagoon.

Bottom sealing is still in the experimental/developmental stages. It appears to be theoretically possible, however, it will require further development and methods for addressing the potential problems that have been pointed out.

An alternative to directionally-controlled horizontal drilling is bottom sealing by means of vertically drilling through the lagoon area and injecting grouting under the lagoon. This technique would utilize the jet-grouting technology. The initial steps in bottom sealing using the vertical injection grouting is to lay out a pattern for construction of bore holes. The spacing of the bore holes would be such that the grout injected at the bottom of each bore hole would overlap, forming a continuous uniform layer of low permeability grout under the lagoon. A jet-grouting device would be used in each bore hole and a cavity created under the bottom of the lagoon and grout injected into the cavity. Successive bore holes in accordance with the predetermined grid pattern would be constructed and grout injected until a continuous layer is formed. Figure 45 shows a schematic of how this grouting may be performed (Kitchens, 1980).
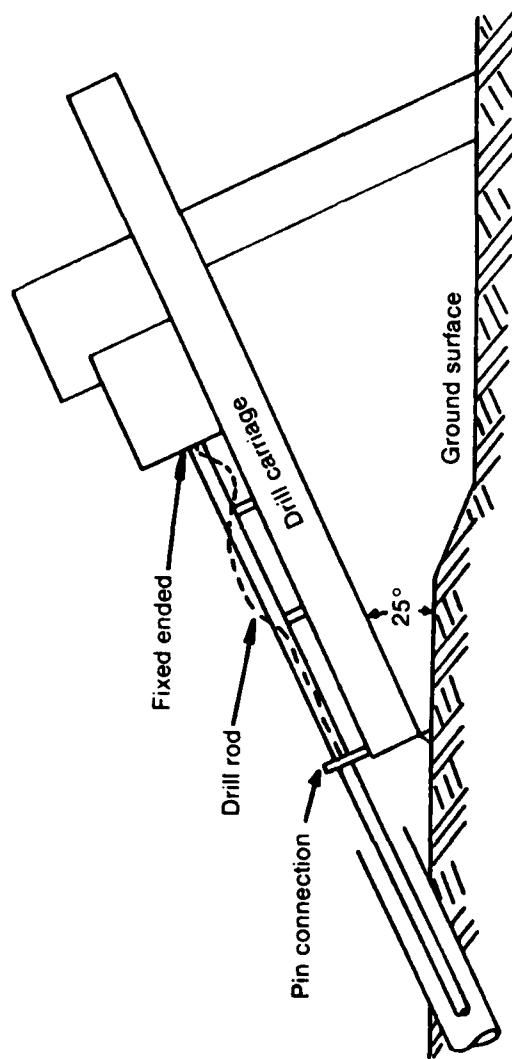
Source: Dowding, 1976; Reading and Bates
Construction Company, 1980; Kitchens, 1980)

Figure 44. Titan contractor's Big Alice drill rig.

Stream

Bore holes

Waste material

5-ft soil layer

Unconsolidated earth materials

Water table

Grouted material

Bedrock
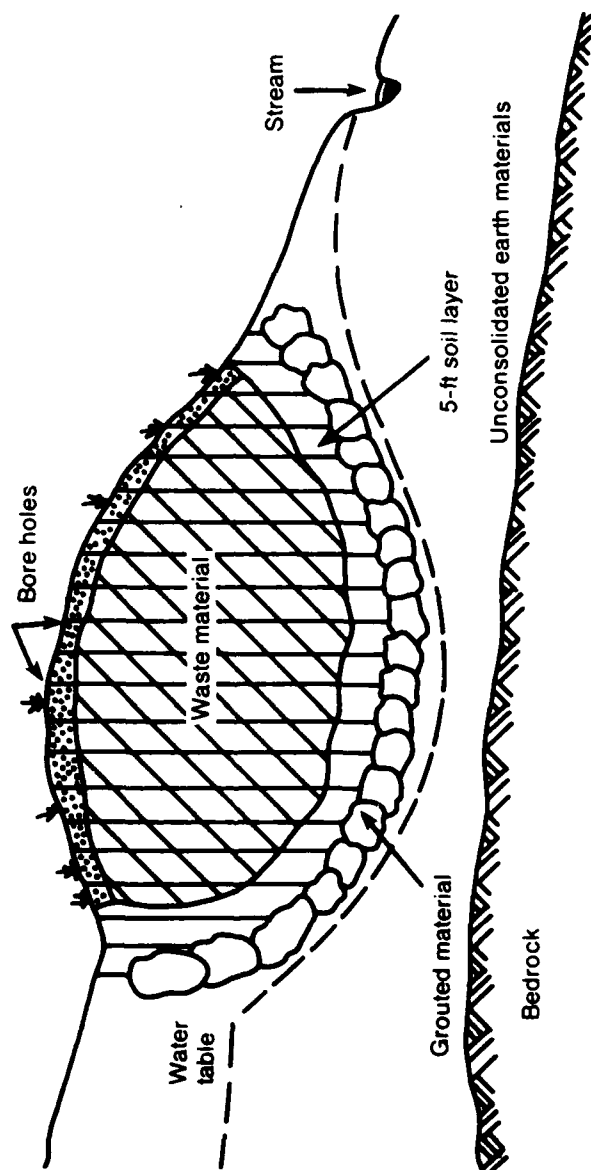
Source: Tolman et al, 1978

Figure 45. Cross-section of grouted bottom seal beneath a containment area.

Several potential problems associated with the vertically placed seal are as follows:

(a)   The drilling rig may have to be supported over the site, which would be a problem if the lagoon contents have no bearing capacity.

(b)   The drilling would occur through the waste, which may cause contamination of lower soil layers as the boring proceeds through the waste under the lagoon.

(c)   Boring through reactive or explosive waste may not be viable.

(d)   It is not possible to verify that a continuous uniform seal would result from the multiple borings and grout injections.

6.4.2.4   Block displacement method.   Block displacement represents a new technique being developed for the in-situ closure of waste disposal sites. This approach utilizes grouting technologies to emplace a liner around the sides and bottom of the disposal area. This technology cannot be considered proven from a historical application standpoint, and is undergoing field development by means of an EPA demonstration program.

The block displacement method is a patented technique using grouting technology. A grout barrier is formed along the sides and bottom of the disposal area using a series of notched injection borings. Through the use of multiple injection points a continuous layer of grout can be constructed. Figure 46 shows a block displacement barrier in place totally encapsulating the sides and bottom of a particular site (Brunsing and Grube).

This technique is particularly applicable to those site conditions where an impermeable confining layer aquiclude is not sufficiently near the ground surface for a perimeter barrier such as slurry wall to provide site containment. In fact, the block displacement method can be used to construct a liner under a site where one does not currently exist.

The perimeter grouted section is first constructed using one of several techniques such as a slurry wall, vibrating beam, or drill notch and blast techniques. This perimeter section of a slurry wall can then be surcharged to ensure a positive horizontal stress in the formation. This is shown on Figure 47 (Brunsing and Grube).
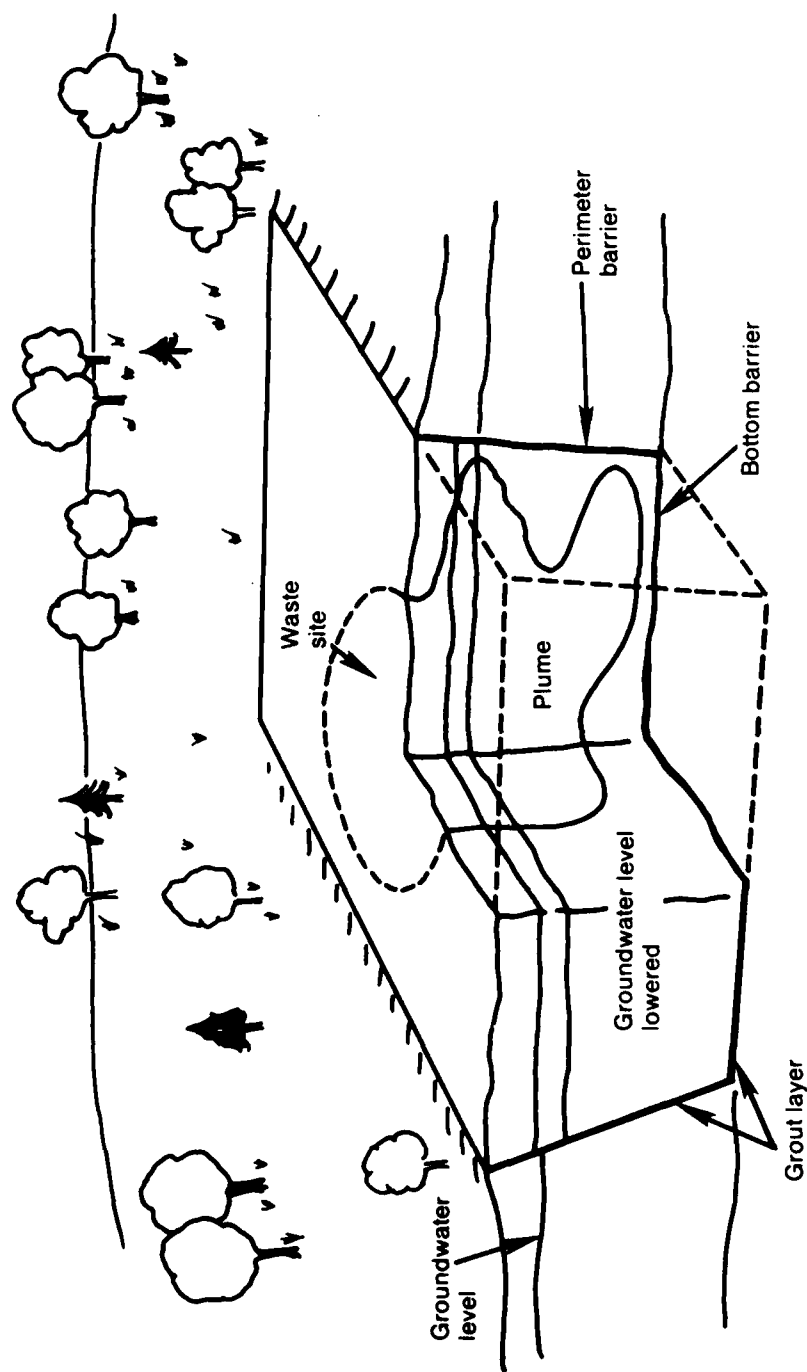
Source: Brunsing and Grube

Figure 46. Block displacement barrier.
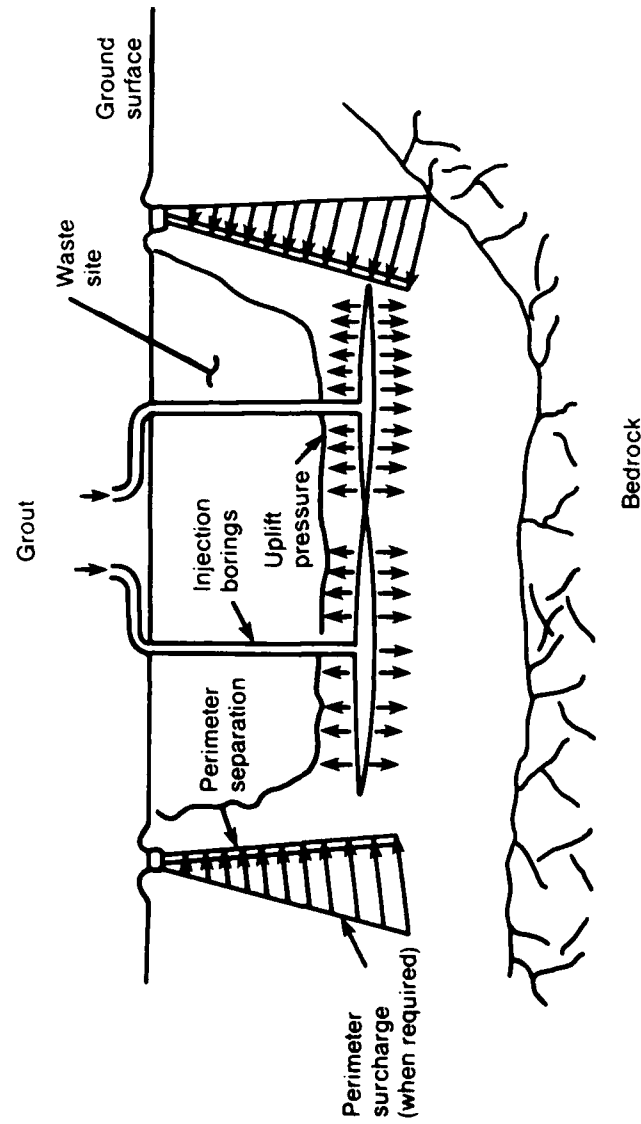
Figure 47. Perimeter section and bottom barrier construction.

Source: Brunsing and Grube

Construction of the bottom barrier then can be initiated and will progress in the following four phases:

(a) Construction of injection borings through the waste site and formation of injection holes under the site using a slurry jet notching tool.

(b) Injection of grout into the notched holes formed by the slurry jet.

(c) Further addition of slurry at each injection point to create a single larger bottom separation so that the injection holes coalesce into a large tenuous separation under the site.

(d) Continuous pumping of slurry to produce a complete layer of grout under the site by controlled further displacement of the earth mass using low pressure slurry injection into the horizontal separation.

Each of these four phases is conducted through controlled monitoring of the slurry pressure, the flow rate of the slurry, the slurry composition and viscosity, and the total volume of slurry injected. Through this controlled block displacement the thickness of the grout layer under the site can vary from a few centimeters to more than a meter. The thickness can be increased by additional pumping of slurry down the injection points. The continuity of the bottom layer of slurry can be verified and checked by monitoring pressure communication between injection points, and by topographic survey of the surface of the site during the displacement operation.

Figure 48 illustrates the final block displacement configuration showing the bottom and perimeter slurry walls. In essence, the terminology block refers to the entire waste disposal site, which is floated on a bed of grout.

While the block displacement technique has shown some promise as a result of EPA's sponsored field demonstration, additional work will be needed to verify the applicability and cost associated with this technology. Additional field demonstration and verification work is needed prior to classifying this approach as a proven technology.

6.4.3 Application potential. A wide range of grouting techniques and materials have been utilized in various geotechnical applications, these include suspension grout methods using clays, cement, and cement clay mixtures. These represent the most widely used grouting materials in geotechnical applications. Chemical grouts are also available, however, these have fewer applications.

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Non-lifting
section of
block

Injection borings

Groundwater
elevation

Displaced block
(waste site)

Perimeter
section

Bottom grout barrier
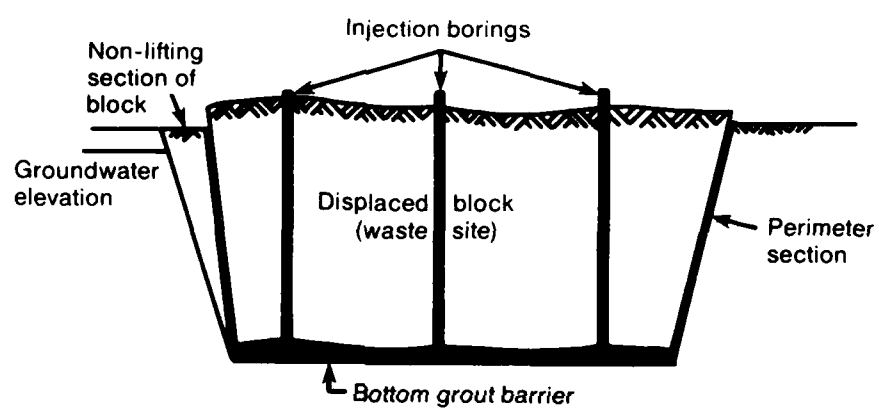
Source; Brunsing and Grube

Figure 48. Final block displacement

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Application of grouting to lagoon closure is, and may continue to be, very limited due to availability of other more cost-effective means of waste isolation. Similar to slurry walls, grouting would rarely, if ever, be used as the sole means of lagoon closure.

Very little information is available on chemical compatibility of grouting materials with various contaminants from existing lagoons at Army installations. Procedures for testing grout compatibility and performance assessment have not been developed.

No data are available on the long-term stability and effectiveness of grouting for waste isolation and contaminant migration control. Determination of the effectiveness of grouting as a means of contaminant isolation is difficult, if not impossible.

Before considering grouting as a means of waste isolation or in-place closure of a lagoon, the following research should be initiated:

(a) Develop protocols for testing grouting materials, the compatibility of grout with contaminants and groundwater, long-term performance, etc.

(b) Tests must be conducted on chemical compatibility of grout materials with the various categories of contaminants found in military installations (easily explosive compounds, solvents, etc.).

(c) A need exists for investigation of the long-term stability and effectiveness of grout material after placement in the ground.

6.5 Sheet piling.

6.5.1 Process description. In addition to the groundwater diversion techniques discussed in the previous subsections relating to grouting and slurry trenching, sheet piling technology may be considered a method for groundwater diversion. Sheet piling construction involves physically driving rigid sheets into the ground to form a barrier to groundwater movement. Typically these sheets are composed of steel or concrete that can be interlocked or sealed to form a continuous impermeable barrier. Steel sheet piling is more commonly used than concrete for groundwater cutoff due to a generally lower cost and capability for interlocking between pilings.

As a result, steel sheet piling will be discussed in this subsection.

A steel sheet piling wall is constructed by driving the sheet segments into the ground using a pile driver. The pilings are first assembled along their edges using interlocks before they are driven into the ground. It is necessary to preassemble the piling segments along their interlocking edges to ensure that a good lock between sheets is obtained. The sheet piles are then driven a few feet at a time into the ground along the length of the wall. This sequence is repeated until all the piles are driven into the ground to the desired depth. (EPA, 1982).

6.5.2 Process design methodology. The design of sheet piling walls must consider several basic factors relating to suitable subsurface conditions. These are as follows:

(a) The presence of a continuous aquiclude underlying the site to provide a bottom barrier and for connection of the bottom of the sheet piling.
(b) Compatible groundwater quality that will not result in rapid degradation (corrosion) of the sheet piling material.
(c) Suitable soil materials to allow the sheets to be physically driven into the ground.

In a manner similar to the other groundwater diversion techniques, sheet piling can be used as a passive control measure to divert groundwater away from the site or contain a leachate plume under a site. The sheet piling may be used in combination with an active groundwater manipulation technology such as pumping or trench collection. A typical cross section of a sheet piling containment is shown on Figure 49.

Sheet piles are normally available in lengths ranging from 4 to 40 feet. A special order may be available in longer lengths. Manufacturers and suppliers of sheet piling generally offer their own shape of piling and type of interlock. Various shapes are depicted on Figure 50. The widths of the sheets for piling generally range from 15 to 20 inches (EPA, 1982).

The design layout for a sheet piling system should consider a depth at which the aquiclude under the site is located and the total length or perimeter for the sheet piling wall. If the aquiclude is located at a depth greater than 40 to 50 feet, sheet piling may not be economically feasible. For large sites requiring a significant length of cutoff wall the number of sheet sections escalate along with the cost.

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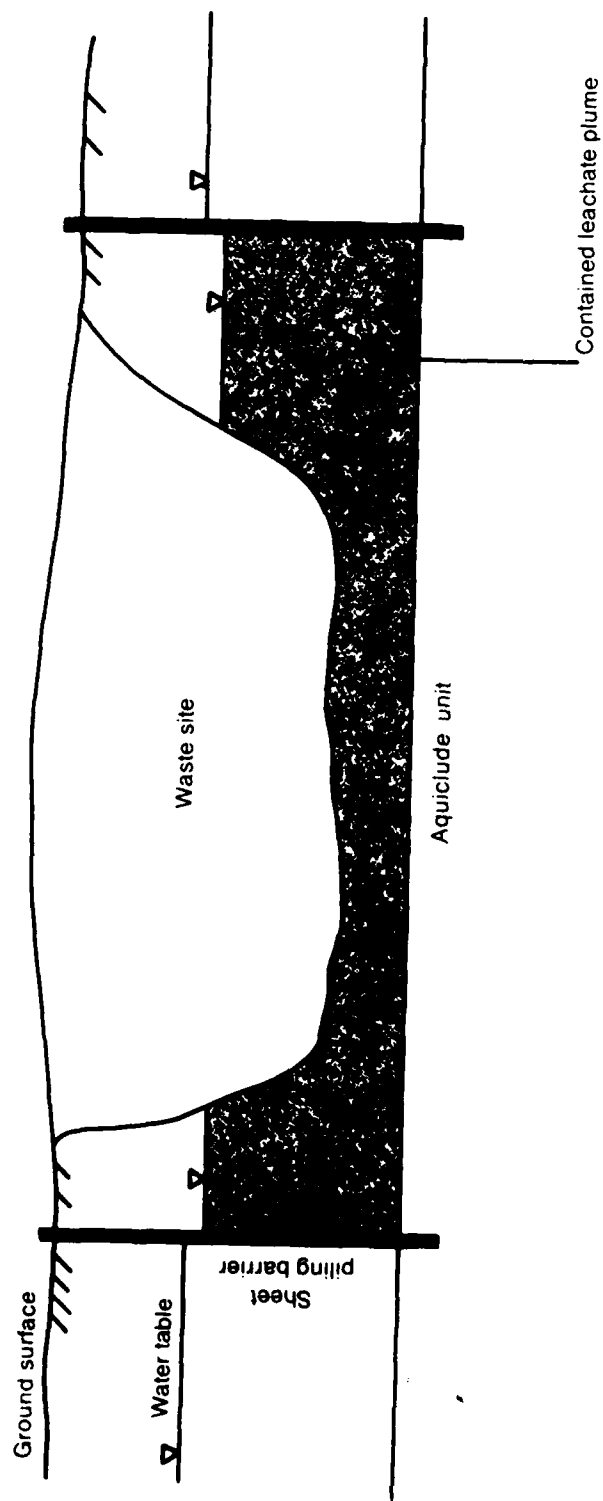
Figure 49. Typical cross-section of sheet piling containment.

Ground surface

Water table

Sheet
piling barrier

Waste site

Aquiclude unit

Contained leachate plume

Straight web type

Arch web type

Deep arch web type

Z-type
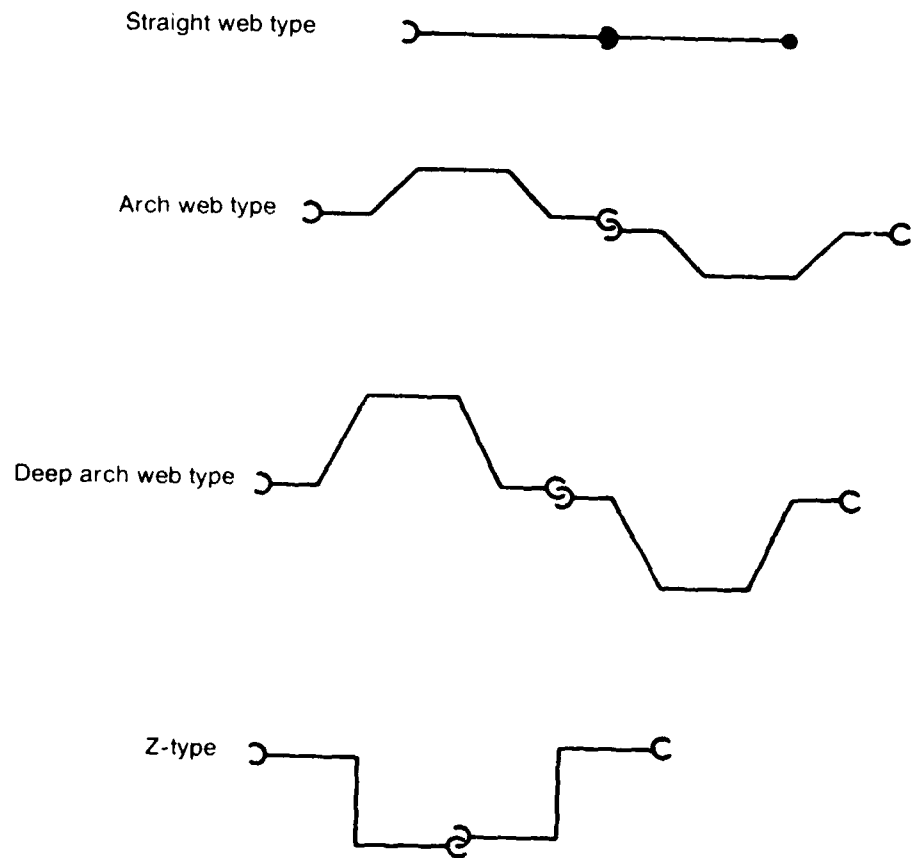
Source: Ueguhart, 1962; EPA, 1982

Figure 50.   Some steel sheet piling shapes and interlocks.

Sheet piling walls will generally not form an impermeable cutoff wall immediately after they are driven into the ground. The interlocks between sheets are not watertight and incorporate ample clearance to allow proper driving and placement into the ground. Over time finer particles of soil are transported by the movement of groundwater and these particles are eventually entrained in the interlock seams. The entrainment of these finer particles forms a seal along the interlocks. This sealing requires a period of time that is dependent on the rate of groundwater migration and the type of soil involved. Very course sandy soils may not form a proper seal, and in these cases, the piling interlocks may require grouting for proper cutoff of water flow.

This time delay in effecting a complete cutoff of groundwater movement must be considered within the overall schedule for closure of a site. If groundwater flow must be diverted within a relatively short time frame with minimal leakage through the wall, then sheet piling may not be a primary candidate.

The performance life of steel sheet piling is generally relatively short compared to other groundwater diversion measures. This performance life may range between 10 and 50 years, depending on the characteristics and environment of the subsurface soils, groundwater, and leachate. Some level of protection of the steel sheet piling from corrosion attack may be achieved by using galvanized, coded, or other special alloy sheet.

As noted, the use of sheet piling is dependent on suitable soil conditions at the site. Soils containing large rocks or boulders may not be suitable for driving the sheet piling. Driving the sheet piles through very rocky soils may damage the piles, which could render the walls ineffective and prevent proper sealing of the seams.

Sheet piling technology is well proven in the construction industry. The technology for installing sheet piling is readily available and contractors are familiar with installation techniques. For some applications, the use of sheet piling may be relatively inexpensive compared to other groundwater diversion techniques. However, the use of sheet piling is dependent on suitable site conditions and will require a period of time for the seams between the sheets to form a seal. The long-term integrity of sheet piling, when exposed to leachate from explosive wastes, is not known. Compatibility data on other types of leachates and steel sheet piling are also limited. The use of sheet piling may be a viable "short-term" control measure until the long-term integrity questions can be resolved.

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7. GROUNDWATER FLOW MANIPULATION

7.1 System description.

7.1.1 Overview. Various groundwater flow manipulation techniques exist as methods of environmental isolation. In many waste management situations, the control of groundwater beneath the site is of crucial concern to an in-place closure strategy. Of course, the site conditions, soils, and geology must be suitable for pumping for this option to be considered. In general, groundwater manipulation or pumping will be more applicable to those soils with a high hydraulic conductivity (e.g., sandy soils) than those with a low conductivity, such as clays and silty clays.

Through groundwater flow manipulation, the location and path of the groundwater table can be altered or contaminated groundwater can be captured. This section describes the applications of groundwater pumping for active flow manipulation. These pumping approaches reflect the active diversion of groundwater as opposed to "passive" approaches such as installing impermeable barriers or permeable interception trenches (passive groundwater controls are discussed in Section 6). The applications discussed herein include the following:

(a)   Pumping to adjust the groundwater table.
(b)   Pumping to contain or capture a contaminant plume.

Active groundwater control techniques rely on the manipulation of groundwater flow patterns. There are essentially two ways to achieve this flow alteration. One method is groundwater extraction, whereby a "cone of depression" is created in the zone of saturation. Extraction techniques can be incorporated to hydraulically alter groundwater flow patterns or to contain or capture contaminated plumes. The second principal method for active groundwater flow manipulation is through injection, whereby a groundwater mound is created. Injection techniques can be used to provide reversed or lower hydraulic gradients to isolate the site or as a part of a groundwater extraction/treatment/injection program.

Groundwater extraction is normally accomplished through a system of shallow or deep pumping wells. The intent is to lower the static water level, thereby reducing the hydraulic gradient

and induce groundwater flow toward the well point(s). In the case of groundwater mounding, the most common technique incorporates a system of shallow or deep injection well points. Active groundwater manipulation is operationally intensive and normally requires long-term continuous operation to be successful, unlike the groundwater diversion techniques of cutoff walls, grout curtains, etc.

7.1.2 Water table adjustment. The controlled adjustment of an underlying water table can be an effective method of hydraulically isolating a waste site and preventing further contamination of groundwater. Continuous groundwater extraction through well points creates a cone of depression around the well point, thereby lowering the water table and inducing groundwater flow toward the well point. Proper placement of extraction wells in close proximity creates a depression network in which the combined cones of depression lower the effective elevation of the groundwater. Extraction pumping to lower the water table may be a suitable measure, as part of an inplace closure strategy, under several conditions. Specific applications may include the following (JRB Associates, 1982):

(a) Lowering the water table, which may be within the contaminated area so that it is no longer in direct contact with the waste material (see Figure 51).

(b) Lowering the water table to prevent leaky aquifers from contaminating other water-bearing areas (see Figure 52).

(c) Lowering an unconfined aquifer sufficiently to prevent the discharge of groundwater to a hydraulically-connected receiving stream (see Figure 53).

If the extraction pumping system intercepts a contaminant plume, then the groundwater being removed will likely be contaminated. In these cases, treatment of the water from the pumping wells will likely be required prior to ultimate discharge. If the quantities of groundwater being pumped are substantial, this treatment operation will be significant and may result in the generation of a sludge that will require disposal.

7.1.3 Contaminated plume containment. Plume containment through groundwater extraction can be an effective means of isolating a waste site and capturing contaminated groundwater to prevent the eventual contamination of drinking water wells, surface water streams, or other aquifers. Plume containment may

Before extraction

Water table

Groundwater flow

Bedrock

After extraction

Pumping

Water table

Bedrock
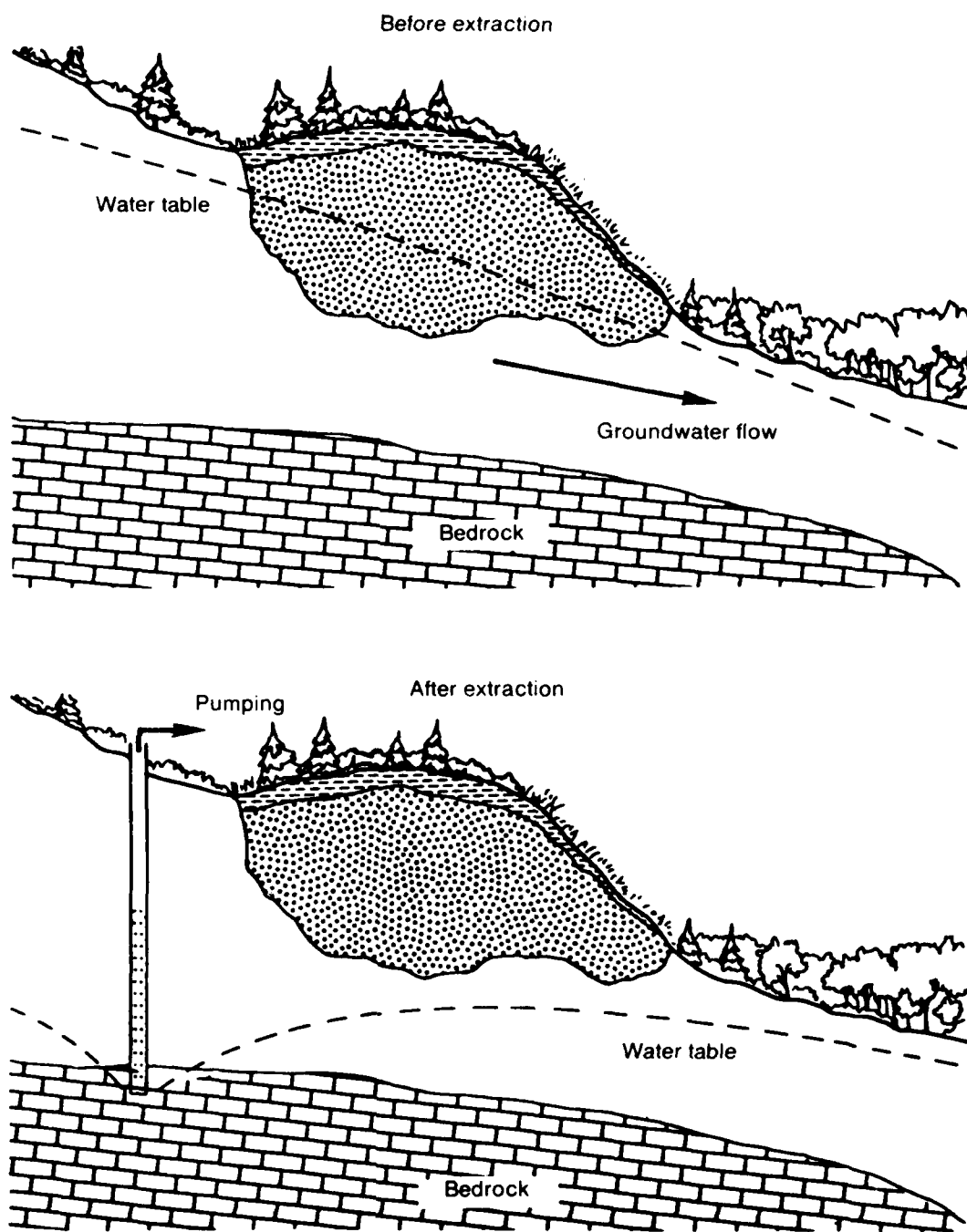
Source: J.R.B. Associates, 1982

Figure 51. Groundwater extraction to eliminate
contact with a disposal site.

Before extraction

Water table

Leaky bedrock

Contaminated aquifer

After extraction

Pumping

Pumping
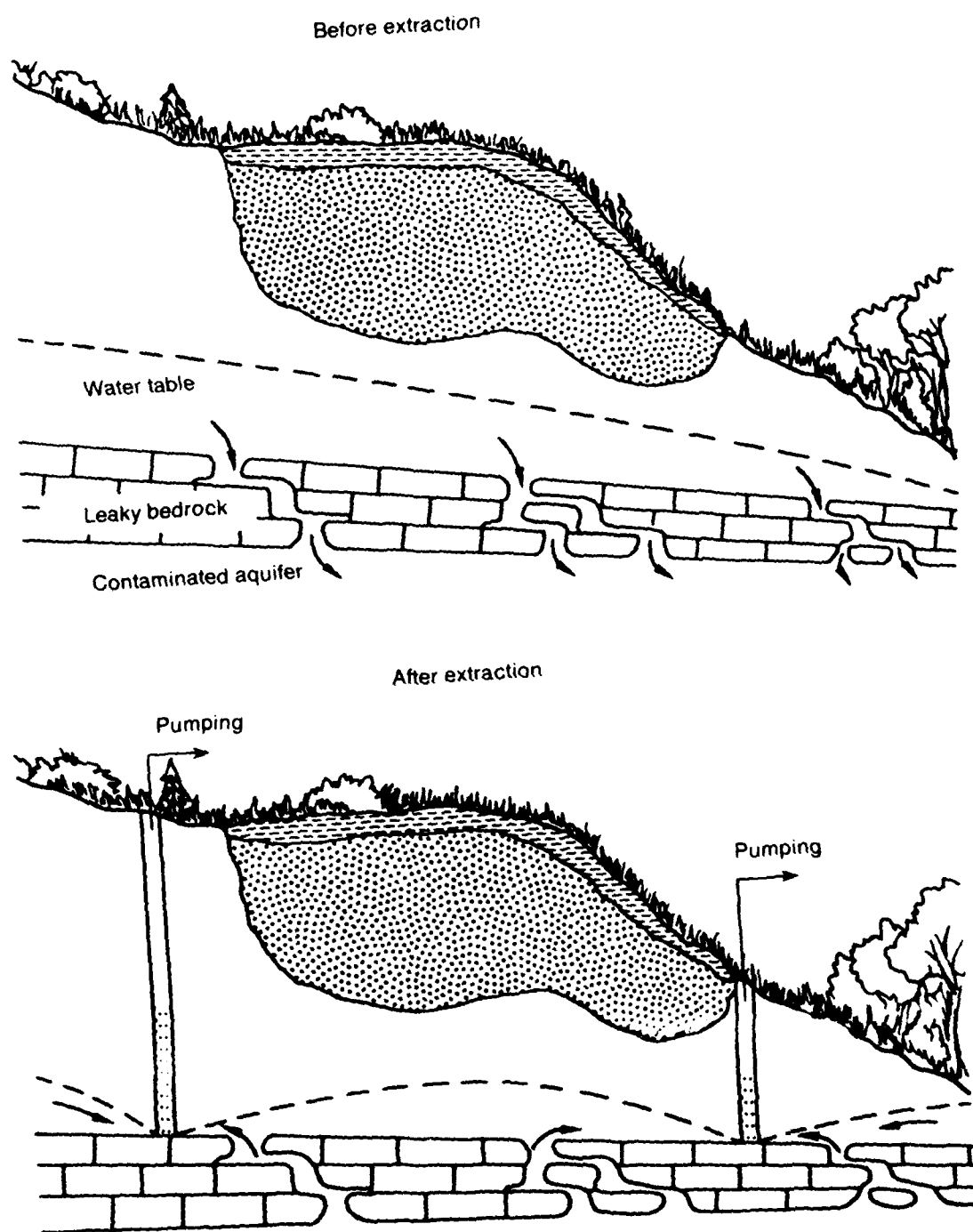
Source: J.R.B. Associates, 1982

Figure 52. Groundwater extraction to prevent contamination of an underlying aquifer.

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Before extraction

Water table

Water-bearing sands

Groundwater flow

Stream

Bedrock

After extraction

Pumping

Water table

Water-bearing sands

Stream

Bedrock
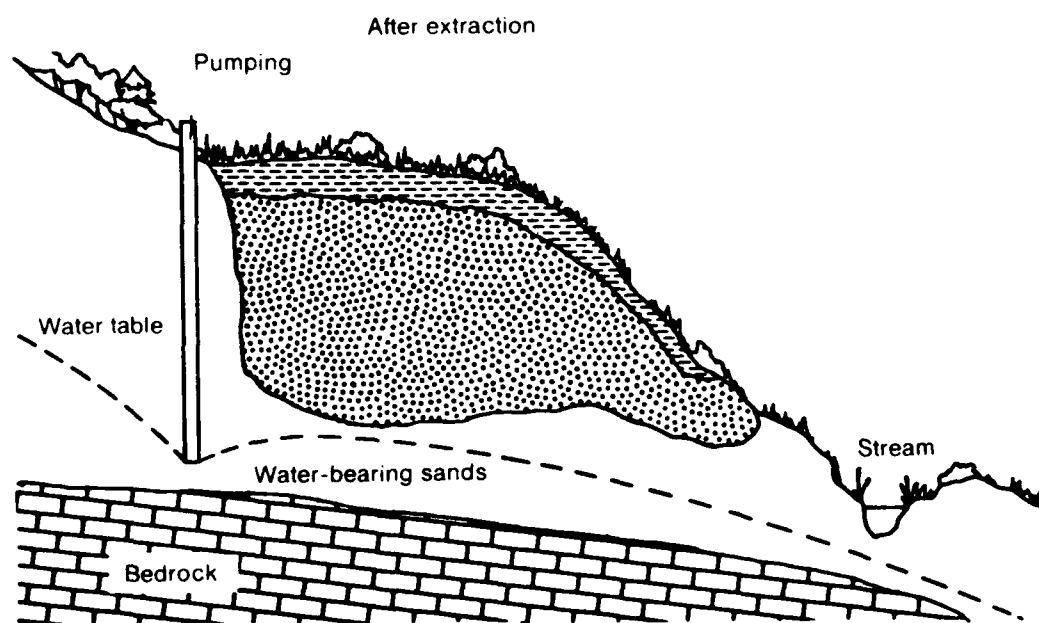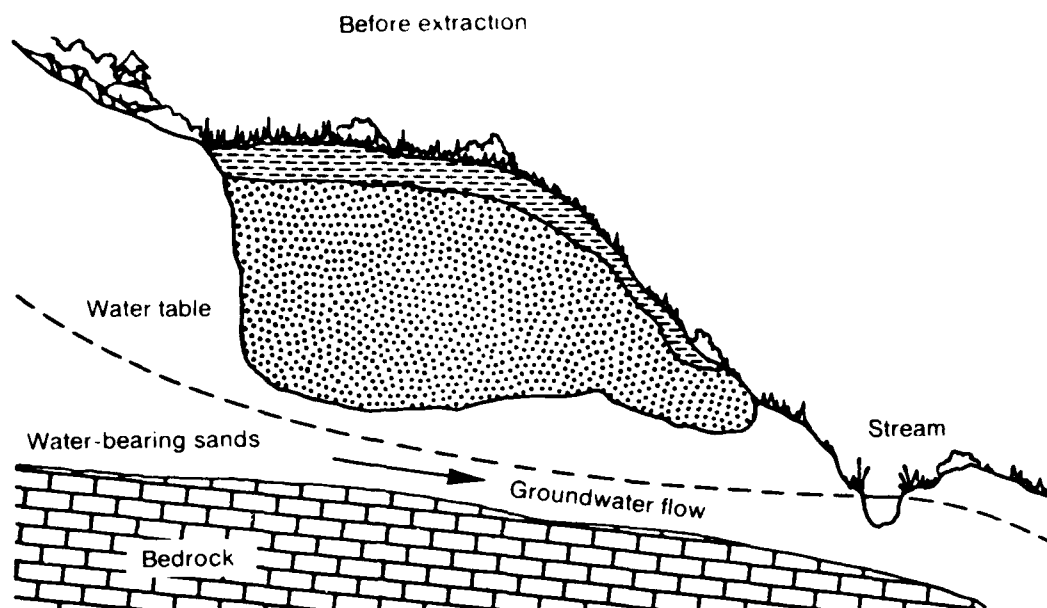
**Figure 53. Groundwater extraction to prevent
contaminated stream discharge.**

be accomplished through extraction alone, where smaller quantities of contaminated groundwater are involved, or through a combination of extraction and recharge or extraction and passive groundwater controls. Recharge may incorporate either injection wells or surface seepage basins. Passive controls used in combination with active controls may include slurry walls or grout curtains. These passive control measures are presented in Section 6, and they will not be reviewed in detail in this section.

Where large groundwater flows are involved or where residents are dependent on groundwater for drinking supplies, recharge or passive controls may be a necessary component of waste isolation. Without aquifer recharge or passive controls, pumping large volumes of contaminated groundwater may lead to significant changes in the water table elevation and may alter the direction of flow.

Plume containment techniques may be incorporated as part of an in-place closure strategy under the following applications (JRB Associates, 1982):

(a) Contaminated groundwater extraction alone (low rates of pumping) with no recharge to the aquifer (see Figure 54).

(b) Use of a series of extraction and injection wells to allow controlled pumping from the aquifer, treatment of the contaminanted groundwater, and recharge to re-stabilize aquifer flow characteristics (see Figure 55).

(c) Use of extraction and seepage basins to allow pumping and treatment of the contaminated groundwater followed by recharge to the aquifer using seepage basins (see Figure 56).

(d) Use of extraction and passive controls to allow a more controlled, selective pumping of the contaminant plume (see Figure 57).

7.1.4 Groundwater flow prediction. Prior to designing any groundwater extraction system, a thorough understanding of the aquifer is required. This knowledge will form the basis for the following:

(a) Determining whether the extraction system will be effective: locating cones of depression and overall zone of influence.

(b) Determining the number of well points that will be required.

(c) Locating the well points.

Before extraction

After extraction
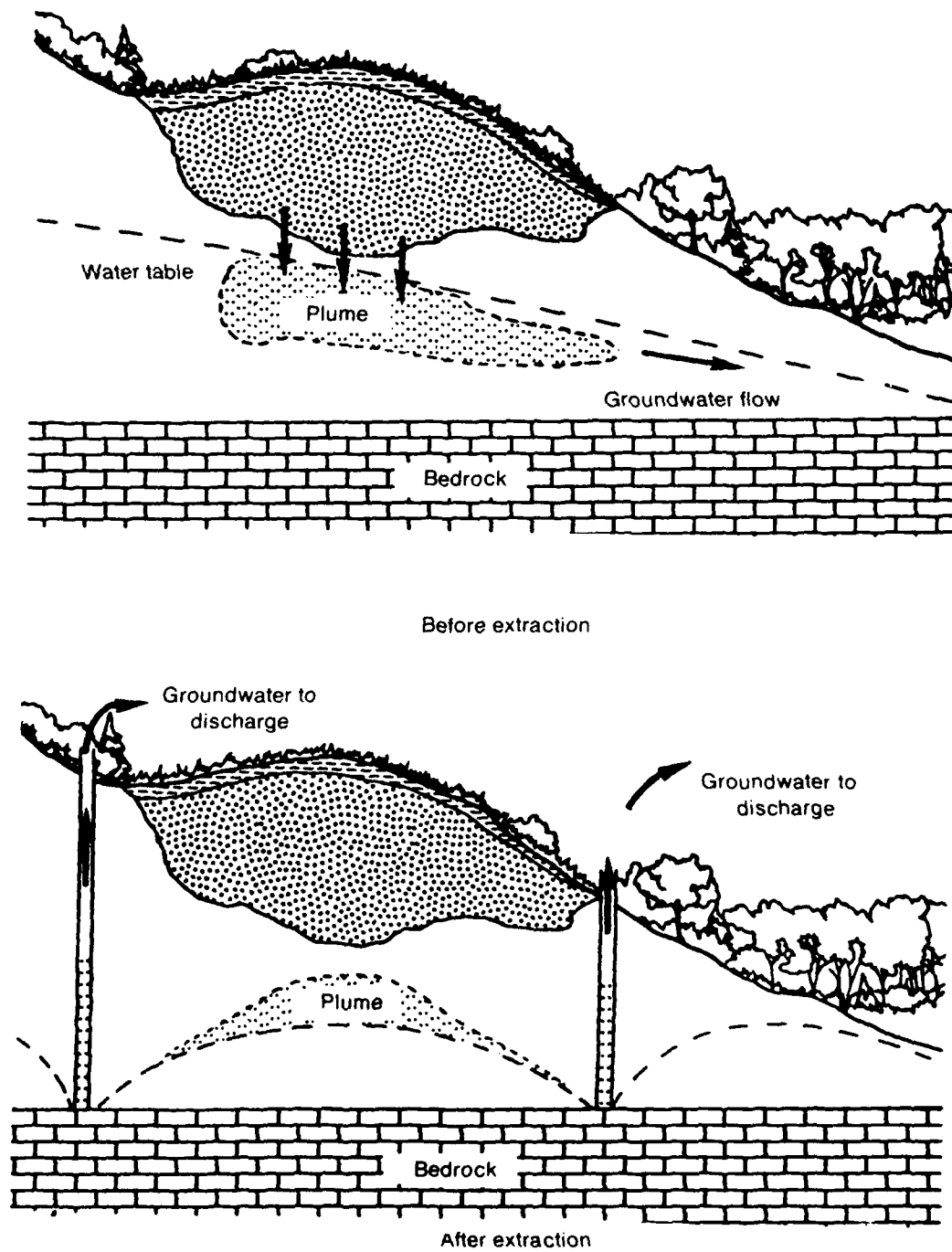
Source: J.R.B. Associates, 1982

Figure 54. Extraction of contaminated groundwater plume.

Water table

Plume

Groundwater flow

Bedrock

Before extraction

Extraction well

Extraction well

Injection well

Plume

Bedrock

After extraction
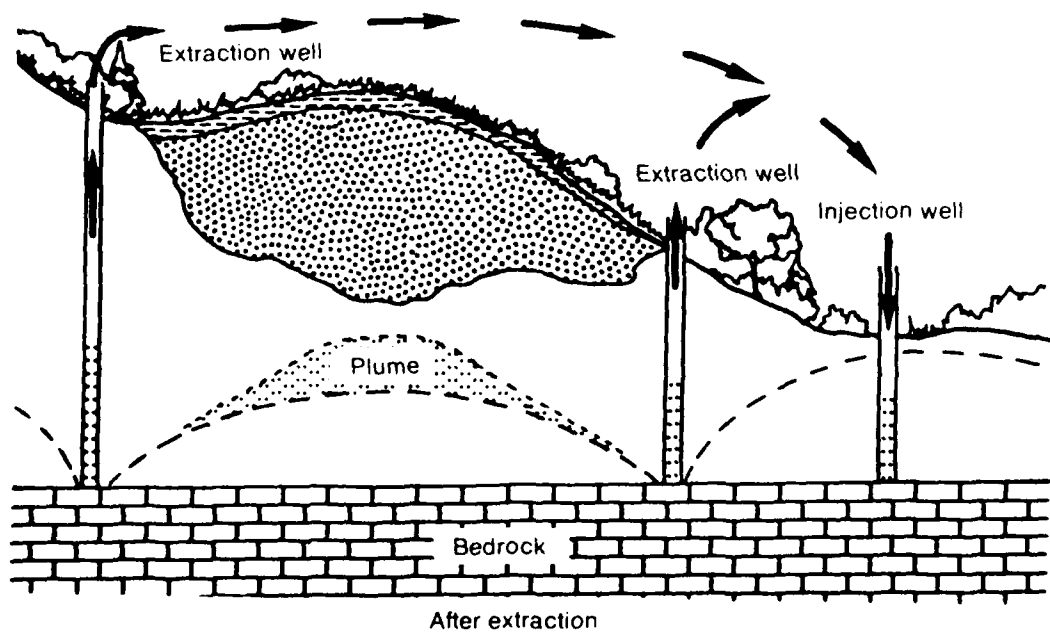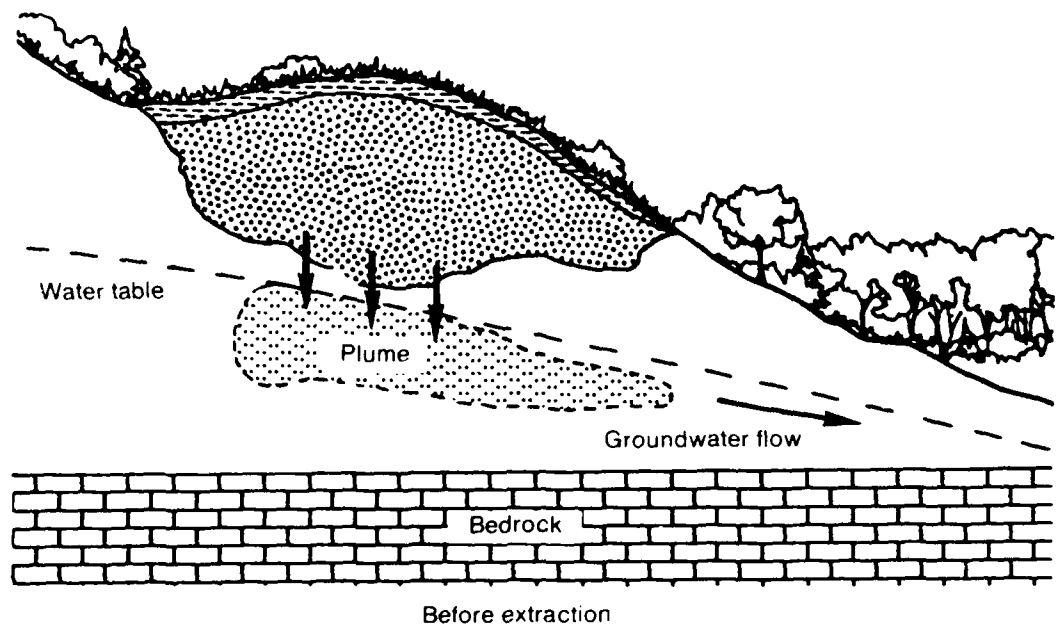
Source J.R.B. Associates, 1982

Figure 55. Extraction and injection for contaminated plume containment.

Water table

Plume

Groundwater flow

Bedrock

Before pumping

Recharge b

Plume

Recharge
boundary

Bedrock

After pumping
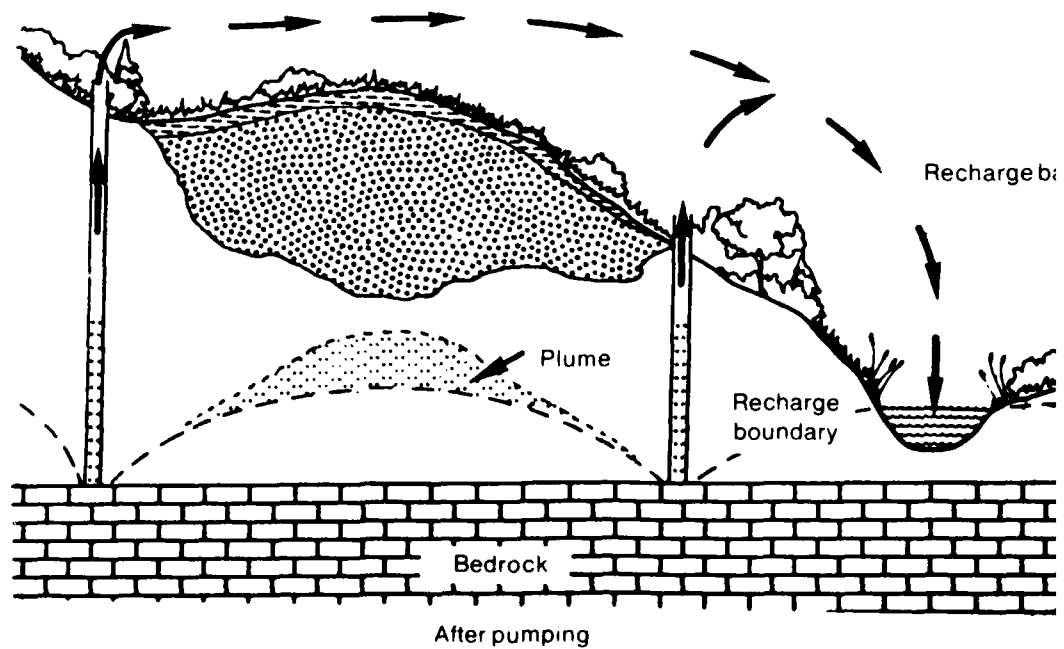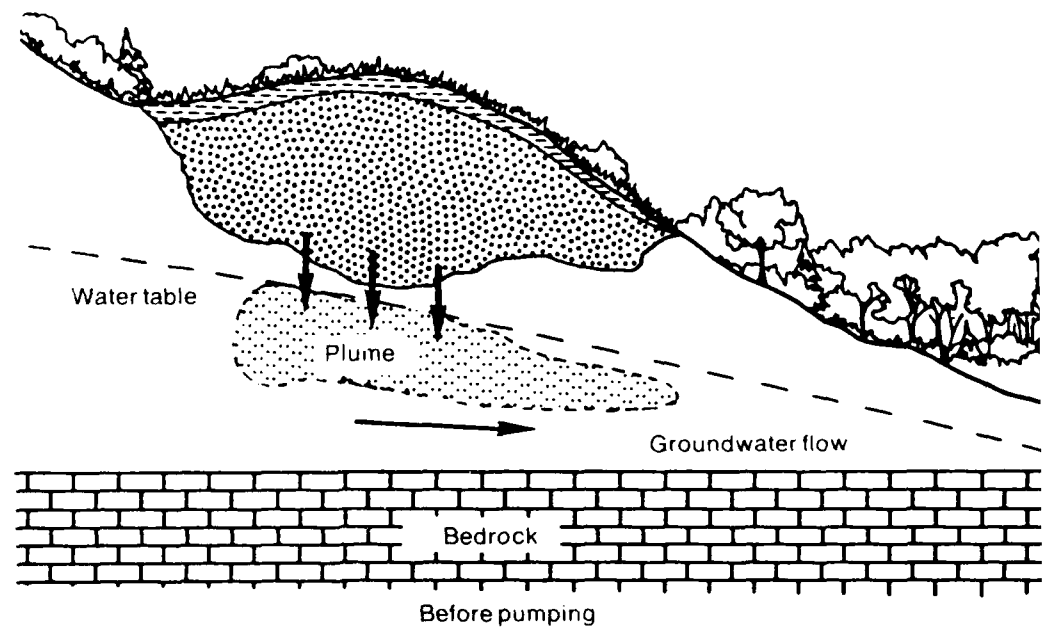
Source. J.R.B. Associates, 1982

Figure 56. Extraction and basin recharge for contaminated plume containment.

Before extraction

During extraction
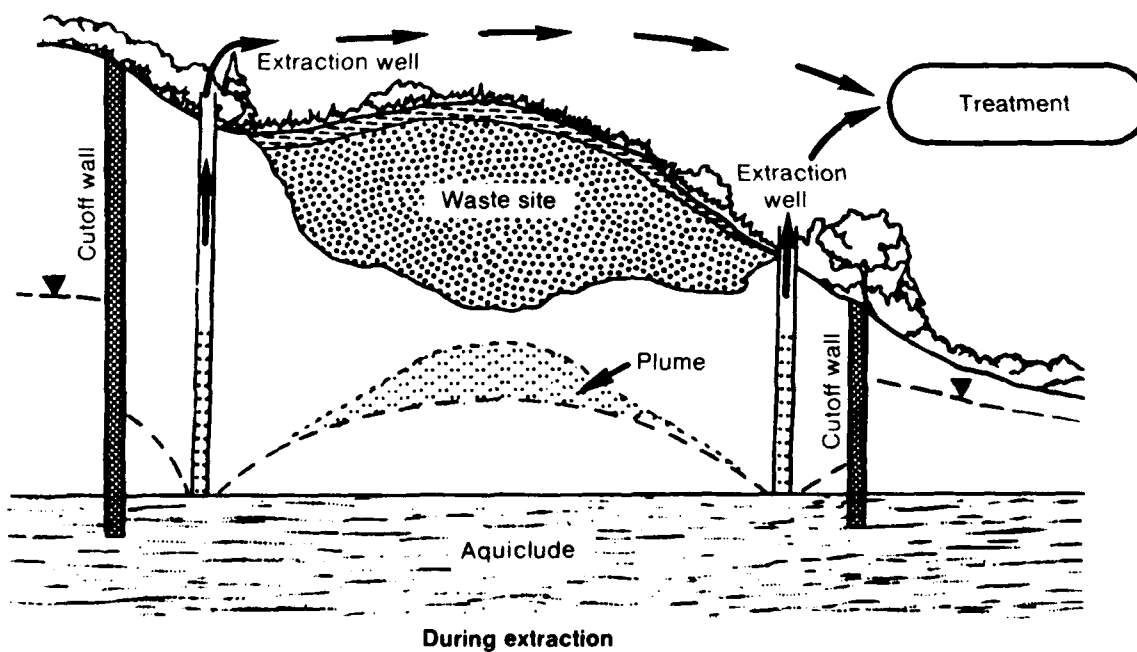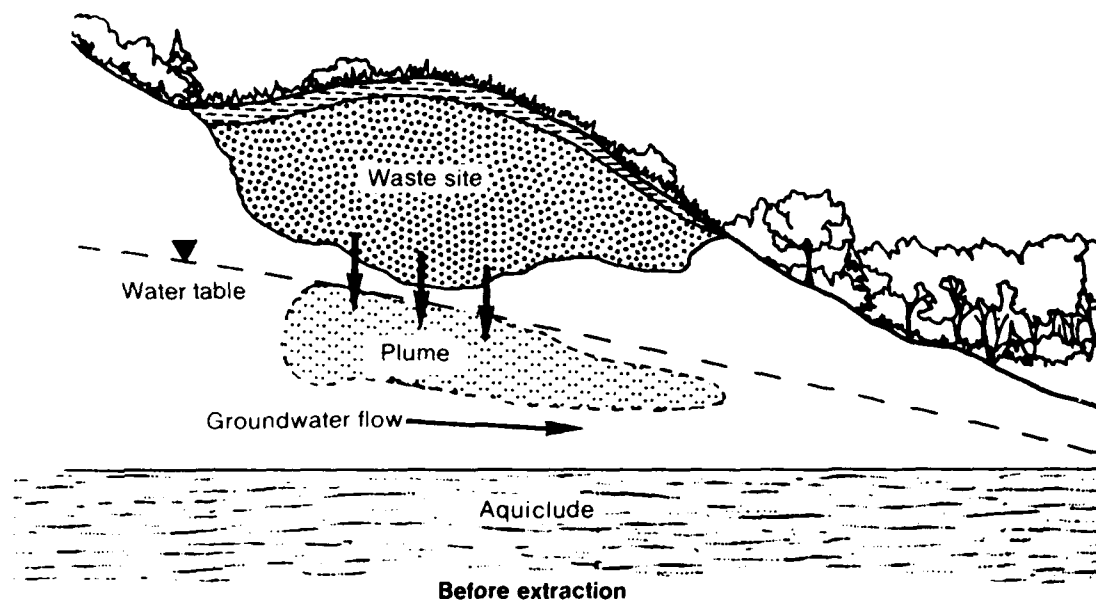
Source: J.R.B. Associates, 1982

Figure 57. Extraction with passive controls for contaminated plume containment.

(d) Determining the depth and design of the well points, including pumping rates.
(e) Estimating the quantity of water to be extracted.
(f) Estimating contaminant concentrations in the extracted water.

When water flows through an open channel or a pipe, the discharge or flow rate (Q, measured as the volume of water flowing in unit time) is equal to the product of its velocity, V, and cross-sectional area of flow, A, shown as follows:

$$Q = VA \tag{15}$$

Prediction of groundwater flow typically involves expressions for flow velocities as a rearrangement of the discharge equation:

$$V = \frac{Q}{A} \tag{16}$$

Groundwater flow prediction is performed using the Darcy equation (or Darcy's law) for laminar flow through a porous medium. Darcy's law assesses the discharge velocity as a function of the soil's ability to pass water (measured as a hydraulic conductivity, k) and the hydraulic gradient of the soil (measured as a unitless ratio of the change in water elevation divided by the change in length, dh/dl). The Darcy equation translates the pipe flow velocity as being the velocity of flow through an equivalent area of pipe filled with a permeable soil, shown as follows:

$$V = \frac{Q}{A} = -k \frac{dh}{dl} \tag{17}$$

The discharge rate calculated by Darcy's law is an apparent velocity, representing the velocity for water movement through an aquifer, assuming the aquifer is an open conduit. In the actual sense, however, the cross-sectional area of flow for a porous medium is much smaller than the aquifer dimensions. To predict groundwater flow through a porous medium, the effective porosity of the aquifer material, n_e, must be considered with the cross-sectional flow area. The effective porosity represents that portion of the soil pore space through which saturated groundwater flow can occur. The true velocity, which is referred

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to as the seepage velocity, reflects the actual flow rate of water moving through the pore spaces and is shown as follows (Fetter, 1980):

$$V_s = \frac{V}{n_e} = \frac{-kdh}{n_e dl} \tag{18}$$

Researchers have discovered that the proportionality constant in Darcy's law (k), which is referred to as the hydraulic conductivity, is a function not only of the porous medium but also of the fluid characteristics. Experiments have shown that particle diameters of the flow medium, fluid density, and dynamic viscosity, as well as hydraulic gradient, are variables in calculating groundwater flows (Hubbert, 1940). When these variables are incorporated into Darcy's law, the expression for discharge velocity is shown as follows (Freeze and Cherry, 1979):

$$V = \frac{-k \, \rho}{\mu} \frac{dh}{dl} \tag{19}$$

Where: k = Intrinsic permeability of the flow medium.
               ρ = Fluid density.
               q = Force of gravity.
               μ = Fluid dynamic viscosity.

7.2 System evaluation methodology.

7.2.1 Background. To evaluate the design and effectiveness of a groundwater flow manipulation system, an assessment must be made of groundwater contamination potentials and the response of the aquifer to pumping. This section presents the methodology for evaluating groundwater flow manipulation through a description of the important considerations for these two factors. Through such an evaluation, the extent of potential groundwater contamination is estimated, and the potential application of an active pumping strategy can be considered.

7.2.2 Assessment of groundwater contamination. Contamination of subsurface aquifers and groundwater drinking supplies can result from the leaching of pollutant compounds from a lagoon area through predominantly physical and chemical phenomena. To assess groundwater contamination, pollutant transport processes must be understood. Differential equations are used to

describe the transport of solutes in porous media, by consider-
ing the concentration flux movement into or out of a fixed ele-
mental volume of fluid. The conservation of mass theorum ad-
dresses this transport process and can be described as follows
(Freeze and Cherry, 1979):

$$
\begin{bmatrix} \text{Net rate of} \\ \text{change of mass} \\ \text{of solute with-} \\ \text{in the element} \end{bmatrix} = \begin{bmatrix} \text{Flux of} \\ \text{solute out} \\ \text{of the} \\ \text{element} \end{bmatrix} - \begin{bmatrix} \text{Flux of} \\ \text{solute into} \\ \text{the} \\ \text{element} \end{bmatrix} \pm \begin{bmatrix} \text{Loss/gain} \\ \text{of solute mass} \\ \text{due to} \\ \text{reactions} \end{bmatrix} \quad (20)
$$

Advection and hydrodynamic dispersion are processes that
control flux movement of contaminants in the groundwater. Advec-
tion is attributed to groundwater velocity, while dispersion oc-
curs as a result of mechanical mixing and diffusion on a molecu-
lar scale. The advection/dispersion equation (shown as follows
in the one-dimensional form) represents the key differential
equation to describe transport processes in groundwater (Freeze
and Cherry, 1979).

$$
D_l \frac{\delta^2 C}{\delta l^2} - V_l \frac{\delta C}{\delta l} = \frac{\delta C}{\delta t} \quad (21)
$$

Where: D_l = Coefficient of dispersion along the flow path
(in longitudinal direction).

C = Solute concentration and $\frac{\delta C}{\delta t}$ is the potential
differential of concentration with respect to
time.

l = Length along the flow line.

V_l = Average linear velocity (equals velocity di-
vided by porosity).

To predict the concentration of a dissolved chemical consti-
tuent in a saturated homogeneous porous medium at any point away
from the source of contamination, the solution of the advection/
dispersion equation can be used as follows (Ogata, 1970):

$$
\frac{C}{C_o} = \frac{1}{2} \left[erfc\left(\frac{l - V_l t}{2\sqrt{D_l t}} \right) + exp\left(\frac{V_l l}{D_l} \right) erfc\left(\frac{l + V_l t}{2\sqrt{D_l t}} \right) \right] \quad (22)
$$

Where: C_o = Initial solute concentration.
erfc = Complementary error function.

Equations 21 and 22 are useful for the interpretation of laboratory column experiments, but have limited application to the nonhomogeneous conditions found in aquifer systems. Three-dimensional predictive equations should be used since dispersive movement in the groundwater occurs in the transverse directions as well as the longitudinal direction. As contaminants are introduced into the porous aquifer at an intial point, they are transported through the flow system, exhibiting a three-dimensional concentration distribution. The concentration of the contaminant mass at a given time, t, is given as follows (Baetsle, 1969):

$$C(x,y,z,t) = \frac{M}{8(\pi t)^{3/2} \sqrt{D_x D_y D_z}} \exp\left(-\frac{x^2}{4D_x t} - \frac{y^2}{4D_y t} - \frac{z^2}{4D_z t}\right) \quad (23)$$

Where: M = Mass of introduced contaminant = $C_o V_o$.
D_x = Coefficient of dispersion in x-direction.
D_y = Coefficient of dispersion in y-direction.
D_z = Coefficient of dispersion in z-direction.
X = X-direction distance from contaminant center of gravity.
Y = Y-direction distance from contaminant center of gravity.
Z = Z-direction distance from contaminant center of gravity.

The mass of the contaminant introduced is given by the product of the initial concentration, C_o, and the initial volume of the contaminant plume, V_o. Peak concentrations are typically of concern in the prediction of groundwater contamination. The peak contaminant concentration, referenced as C_{max} occurs at the center of gravity of the contaminant plume and can be shown as follows (Baetsle, 1969):

$$C_{max} = \frac{C_o V_o}{8(\pi t)^{3/2} \sqrt{D_x D_y D_z}} \quad (24)$$

While these equations take into account dispersive and advective transport in all directions, they are based on idealized conditions, such as an instantaneous point source of contamination and uniform groundwater flow. As such, these equations have

limited use in the analysis of most aquifer situations, and may be appropriate only to obtain preliminary estimates of contaminant migration patterns. Site-specific conditions may introduce errors into calculations of groundwater contamination based on equations 23 and 24. Some of these factors may include the following (Freeze & Cherry, 1979):

(a) Density contrasts between the groundwater and the contaminated plume.
(b) Heterogeneous soil media of varying permeabilities.
(c) Boundary effects in the porous media.
(d) Transport phenomena in a fractured medium (bedrock).
(e) Transport of reactive constituents (the presented advection/dispersion equation does not incorporate the loss or gain of solute due to chemical or biological reactions).

7.2.3 Response of aquifers to pumping. Within a waste isolation strategy that incorporates groundwater pumping, an assessment must be made of the aquifer's hydraulic response to various extraction and injection strategies. Under static conditions without pumping, the groundwater surface elevation remains essentially constant with normal seasonal variations due predominantly to climatic conditions. Pumping introduces hydraulic gradients sloping toward the well, thereby lowering the overall hydraulic head as a three-dimensional cone-like depression surrounding the well point. When a well is pumped at a constant rate, the influence of the extraction extends outward with time. The methodology for evaluating this cone of depression or "drawdown" is based on the partial differential equation shown as follows, and is graphically presented on Figure 58. This equation describes saturated flow in two horizontal dimensions within a confined aquifer (Todd, 1980; Freeze and Cherry, 1979).

$$\frac{\delta^2 h}{\delta r^2} + \frac{1}{r}\frac{\delta h}{\delta r} = \frac{S}{T}\frac{\delta n}{\delta t} \qquad (25)$$

Where:
h = Pressure head.
r = Radial distance from the pumped well.
S = Storage coefficient = $S_s b$; specific storage of aquifer times aquifer thickness.
T = Transmissivity = Kb; hydraulic conductivity of aquifer times aquifer thickness.

Theis (1935) developed an analytical well function solution to equation 25 to describe the hydraulic drawdown that results from well pumping of a confined aquifer.

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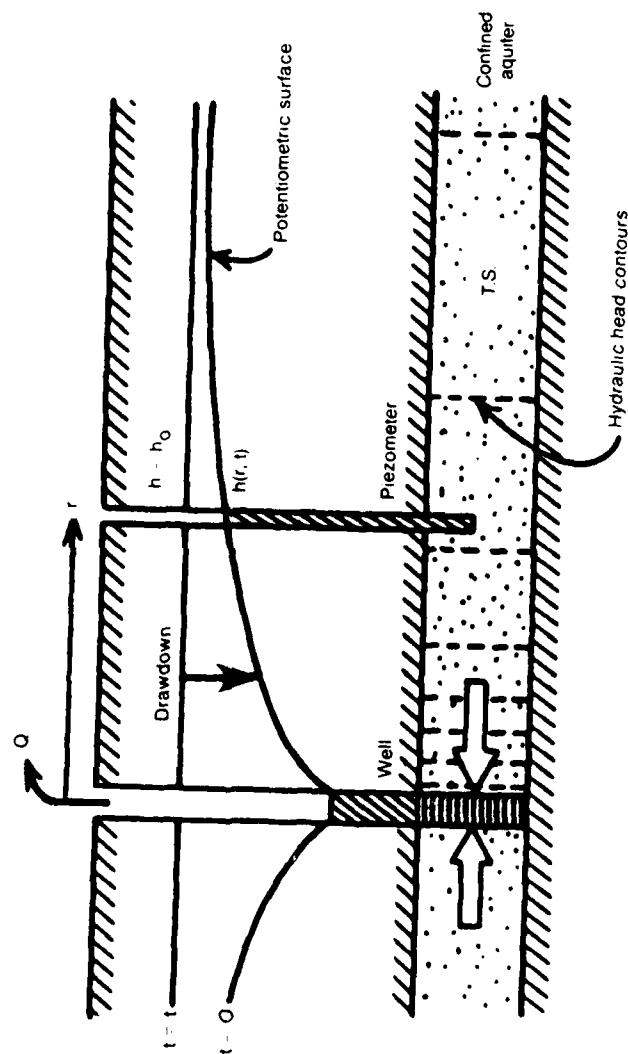
Source: Freeze and Cherry, 1979

Figure 58.   Radial flow within a horizontal confined aquifer.

$$h_o - h(r,t) = \frac{Q}{4\pi t} W(u) \qquad (26)$$

Where: $u = \frac{r^2 S}{4Tt} \qquad (27)$

Once the aquifer properties of transmissivity, T, storage, S, and pumping rate, Q, are known for a particular application, one can predict the drawdown in hydraulic pressure head within the confined aquifer at a specific radial distance, r, from the well at any time, t, after the start of pumping. Once the factor, u, is calculated using equation 27, the well function value of u (referenced as W(u) in equation 26) can be obtained from the tabulated values of W(u) (see Table 29 for well function values).

For a system of "n" number of wells, as in a multiple well field, the Theis solution can be applied to calculate the overall drawdown in the confined aquifer (see Figure 59 for a schematic of a double-well pumping scheme). As shown on this figure, the pumping wells are normally located so that the cones of depression intersect so that an overall zone of influence is achieved. For the well system pumping at rates Q_1, Q_2, Q_3, ...Q_n, the following relation can be used to predict the drawdown at a point whose radial distance from each well is given by r_1, r_2, r_3,....r_n:

$$h_o - h = \frac{Q_1}{4\pi T} W(u_1) + \frac{Q_2}{4\pi T} W(u_2) + \frac{Q_3}{4\pi T} W(u_3) + ... + \frac{Qn}{4\pi T} W(u_n)$$

$$(28)$$

Where: $u_i = \frac{r_i^2 S}{4t_i T}$ and $i = 1$ to n

Geologic configurations may not be as idealized in the confined aquifer situation modeled by the previous equations. Deviations from the Theis solution may occur for time-drawdown responses of the aquifer in the following situations:

(a) Leaky aquifers.
(b) Unconfined aquifers.
(c) Stepped pumping rates.
(d) Bounded aquifers.
(e) Partially penetrating wells.

TABLE 29. VALUES OF THE WELL FUNCTION W(u) FOR VARIOUS
VALUES OF u

u	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
× 1	0.219	0.049	0.013	0.0038	0.0011	0.00036	0.00012	0.000038	0.000012
× 10^{-1}	1.32	1.22	0.91	0.70	0.56	0.45	0.37	0.31	0.26
× 10^{-2}	4.04	3.35	2.96	2.68	2.47	2.30	2.15	2.03	1.92
× 10^{-3}	6.33	5.64	5.23	4.95	4.73	4.54	4.39	4.26	4.14
× 10^{-4}	8.63	7.94	7.53	7.25	7.02	6.84	6.69	6.55	6.44
× 10^{-5}	10.94	10.24	9.84	9.55	9.33	9.14	8.99	8.86	8.74
× 10^{-6}	13.24	12.55	12.14	11.85	11.63	11.45	11.29	11.16	11.04
× 10^{-7}	15.54	14.85	14.44	14.15	13.93	13.75	13.60	13.46	13.34
× 10^{-8}	17.84	17.15	16.74	16.46	16.23	16.05	15.90	15.76	15.65
× 10^{-9}	20.15	19.45	19.05	18.76	18.54	18.35	18.20	18.07	17.95
× 10^{-10}	22.45	21.76	21.35	21.06	20.84	20.66	20.50	20.37	20.25
× 10^{-11}	24.75	24.06	23.65	23.36	23.14	22.96	22.81	22.67	22.55
× 10^{-12}	27.05	26.36	25.96	25.67	25.44	25.26	25.11	24.97	24.86
× 10^{-13}	29.36	28.66	28.26	27.97	27.75	27.56	27.41	27.28	27.16
× 10^{-14}	31.66	30.97	30.56	30.27	30.05	29.87	29.71	29.58	29.46
× 10^{-15}	33.96	33.27	32.86	32.58	32.35	32.17	32.02	31.88	31.76

Source: Wenzel, 1942.

Source: Freeze and Cherry, 1979
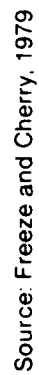
Figure 59.   Drawdown in potentiometric surface of a confined aquifer being pumped by two wells.

One basic assumption of the Theis solution is often not completely met which relates to isolation of groundwater underlying a waste disposal site. This assumption is that an impermeable layer overlies a confined aquifer. The mathematics of the Theis solution do not account for the manner in which groundwater is replenished through infiltration or for the presence of boundaries that limit the extent of the aquifer. Actual drawdown in leaky aquifers is less than that in completely confined aquifers. Use of the Theis equation in leaky aquifer situations to predict water table changes provides a conservative estimate by overpredicting drawdown. A modified solution to the Theis equation can be used to quantify drawdown in leaky aquifers. This solution, as derived by Hantush (1960) and Neuman and Witherspoon (1969), is as follows:

$$h_o - h = \frac{Q}{4\pi T} W(u, r/B) \tag{29}$$

Where: $W(u, r/B)$ = Leaky aquifer well function.

$$r/B = \frac{r}{\sqrt{T/(K'/b')}}$$

K' = Hydraulic conductivity of aquitard.
b' = Thickness of saturated semipervious layer.

Values for the well function, $W(u, r/B)$, have been tabulated and can be readily obtained.

Unconfined aquifers introduce errors into use of the normal Theis solution. Estimates for an unconfined aquifer are complicated by the presence of a vertical flow component, in addition to the horizontal flow components found in confined aquifers (Freeze and Cherry, 1979). Extraction pumping creates a drawdown cone in the entire water table and thus induces the vertical component of flow. Neuman (1972, 1975) developed the unconfined aquifer solutions as shown below:

$$h_o - h = \frac{Q}{4\pi T} W(u_a, u_b, N) \tag{30}$$

Where: $W(u_a, u_b, N)$ = Unconfined aquifer well function N.

$$N = \frac{r^2}{2_b}$$

The design and installation of well-point extraction systems must consider the type of groundwater regime (which determines the specific drawdown equation to use), the transmissivity and storativity of the aquifer, the affected area of the waste site, and the depth to the water-bearing zone. These factors affect the number of extraction or injection wells, the spacing between adjacent wells, the required well depths, the pumping rates, and the size of the pipes.

As discussed, the successful application of a well-point extraction system is dependent on suitable hydrogeological site conditions. If the underlying soils or geology have a low transmissivity, pumping/extraction wells will probably not be effective. The radius of the cone of depression for each well will be too small to intercept the contaminant plume in a cost-effective manner.

7.3 **Environmental performance verification.** The use of the predictive equations described in subsection 7.2 forms the basis of an assessment of groundwater flow manipulation techniques. An equally important component of such an evaluation is the use of environmental performance verification techniques. To determine the actual field response of a groundwater regime to well-point pumping, the specific environmental parameters of hydraulic conductivity, k; soil porosity, n; aquifer transmissivity, T; and aquifer storativity, S; must be verified through laboratory and/ or field analytical methods. This subsection concentrates on the laboratory testing techniques and the field testing techniques of piezometer and pumping tests that can be used to verify the performance of a groundwater flow manipulation strategy.

The typical verification procedure includes the acquisition of representative soil samples for laboratory analysis and the subsequent field placement of exploratory piezometers and well points for pumping tests. The course of events typically incorporated during the initial exploration of an aquifer includes the following (Freeze and Cherry, 1979):

(a) Drilling of a test well with one or more observation piezometers to establish general aquifer characteristics.

(b) Short-term pumping tests to determine empirically the hydrogeological aquifer parameters.

(c) Application of the appropriate predictive equations, developed in subsection 7.2, using the results of the pumping tests to design the extraction/injection well system required to perform groundwater flow manipulation.

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7.3.1 Laboratory tests. Laboratory tests are performed to describe the basic hydrogeological parameters required for groundwater modelling. Laboratory tests are performed on small samples taken as undisturbed soil corings or as representative grab samples to determine the soil's hydraulic conductivity and porosity. These hydrogeological parameters are indicative of the soil in the saturated state, such as with aquifer systems.

7.3.1.1 Hydraulic conductivity. Hydraulic conductivity represents the key factor in the soil's capacity to transmit subsurface water. The hydraulic conductivity (which has a direct relationship to soil permeability) can be measured in the laboratory with two basic types of apparatus. These include the constant-head permeameter (as shown in Figure 60a) and the falling-head permeameter (as shown in Figure 60b). The constant-head unit incorporates a continuous supply of water to provide a constant pressure head differential across the sample, while the falling-head unit incorporates a time-dependent relationship to compensate for decreasing pressure head differentials.

In the constant-head test, a soil sample of length, L, and a cross-sectional area, A, is enclosed in the cylindrical unit, and the head differential, H, is set up across the sample. The volumetric discharge of Q is measured, and a straightforward application of the Darcy equation leads to an expression of the hydraulic conductivity as shown (Freeze and Cherry, 1979):

$$k = \frac{QL}{AH} \tag{31}$$

In the falling-head test, a similar soil encasing arrangement is utilized, and the change in hydraulic head (water level falls from H_0 to H_1,) within a small tube of crosssectional area "a" is measured during an elapsed time, t. The hydraulic conductivity is calculated from the relationship as shown (Freeze and Cherry, 1979):

$$k = \frac{aL}{At} \ln\left(\frac{H_0}{H_1}\right) \tag{32}$$

7.3.1.2 Porosity. Soil porosity is a measurement that relates the volume of pore openings or voids to the total volume of the soil mass. The porosity, n, can be an important controlling influence on the soil's hydraulic conductivity. Generally,

Head falls from H_0 to H_1 in time t

Cross-sectional area a

Soil Sample

Cross-sectional area A

H_0

H_1

L

b. Falling-head permeameter

Continuous water supply

Overflow

Soil Sample

Cross-sectional area A

I

L

Volume V in time t

$Q = V/t$
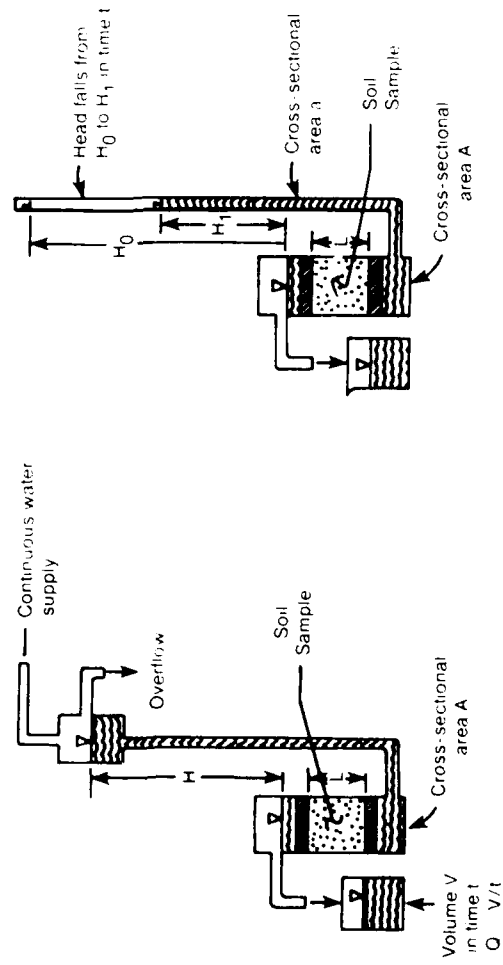
a. Constant-head permeameter

Source: Todd. 1959

soil samples of high porosity also have high hydraulic conductivity. In theory, soil porosity would be measured in the laboratory by saturating a sample, measuring its total volume, V_t, weighing the saturated sample, and oven drying to evaporate the water (Lambe, 1951). The weights of the water would be converted to its volume, and this would be equivalent to the volume of the void space, V_v. Porosity could be calculated from the following relation (Lambe, 1951):

$$n = \frac{V_v}{V_t} \tag{33}$$

The difficulty in practice arises from the fact that many soil samples are nearly impossible to saturate. To compensate for this laboratory constraint, a density relationship follows that can be used to calculate porosity (Vomocil, 1965). In the equation, ρ_b is the bulk density, which is a measurement of the oven-dried mass divided by the initial field volume, and the factor ρ_s is the soil particle density, which is a measurement of the oven-dried mass divided by the volume of solid particles.

$$n = 1 - \frac{\rho b}{\rho s} \tag{34}$$

7.3.2 Piezometer tests. Piezometers can be utilized as a field verification method for obtaining in-situ hydraulic conductivity rates. Piezometer tests incorporate short-duration removals or introductions of a known quantity of water to assess the time-dependent recovery of the aquifer. Piezometer tests can incorporate either units that are open at the base for only a short length (point piezometers), or units that are screened over the entire thickness of the confined aquifer.

The interpretation used most commonly to predict the field hydraulic conductivity for a point piezometer was developed by Hvorslev (1951). In terms of a bailing-recovery test (timed removal of water), Hvorslev reasoned that the inflow recovery to the well is a function of the soil's hydraulic conductivity, K, and the unrecovered head difference in the well. The relationship used to calculate K from this testing methodology is as follows (Freeze and Cherry, 1979):

$$K = \frac{r^2 \ln(L/R)}{2\, LT_o} \tag{35}$$

Where: r = Radius of the piezometer.
       L = Length of point piezometer intake.
       R = Radius of point piezometer intake.
       T_o = Basic time lag for the aquifer.

A set of timed field recovery data points are obtained, and a plot of the ratio of unrecovered head difference to the initial head difference ($H-h/H-h_o$) is made. From this plot, an empirical value for the aquifer's basic time lag of recovery, T_o, is obtained.

The test methodology applied to piezometers that are open over the entire confined aquifer thickness was developed by Cooper et al. (1967) and Papadopoulos et al. (1973). The solution parallels the Theis solution for combined aquifer pumping described in subsection 7.2, and utilizes a curve-matching procedure to empirically verify the aquifer parameters of transmissivity and storativity. Once the bailing-recovery tests are complete and the transmissivity, T, is graphically obtained, the relationship that follows is used to calculate hydraulic conductivity in a confined aquifer of thickness, b (Freeze and Cherry, 1979):

$$K = T/b \tag{36}$$

7.3.3 Field pumping tests. Pumping tests represent empirical methods to field verify the aquifer parameters of transmissivity, T, and storativity, S. Pumping tests provide useful information that is more representative of true aquifer conditions than that provided by laboratory and piezometer tests. Laboratory tests provide singular point values of hydrogeological parameters, and piezometer tests provide in-situ values that are only representative of a relatively small volume of the aquifer surrounding piezometer openings. Pumping tests provide the advantages of in-situ measurement while averaging the hydrogeological parameters over a large aquifer volume. Disadvantages of the pumping tests include the costs for performing the field tests and the difficulty in predicting the results.

The formulas presented in subsection 7.2 are applied to pumping tests with empirical values obtained for drawdown, h_o-h, versus time to determine T and S for the aquifer. The methodology used in pumping tests is graphical. The two graphical approaches discussed briefly in this subsection include the Theis method (involving curve matching on a log-log plot) and the Jacob method (involving interpretations from a semilog plot) (Freeze and Cherry, 1979).

7.3.3.1 Pumping tests: Theis method. The Theis graphical method is used in conjunction with a pumping well and an observatory piezometer at some distance away (but within the expected cone of depression of the pumping well). During the pumping, the drawdown is observed in the piezometer, and the following graphical curve-matching procedure is incorporated (Freeze and Cherry, 1979):

(a) Plot the theoretical well response or "type curve" by plotting the well function W (u) versus 1/u on log-log paper.

(b) Plot the observed "field curve" with drawdown values, h_o-h, versus time, t, on a second log-log graph of the same scale.

(c) Superimpose and adjust the field curve with the type curve, keeping the coordinate axes parallel, until the majority of the observed data points fall on the type curve.

(d) An arbitrary match point is selected and the four corresponding values of W(u), 1/u, h_o-h, and t are used in conjunction with the known pumping rate, Q, and the radial distance from the well to the piezometer, r, to empirically calculate T and S using manipulations of equations 25 and 26, shown as follows:

$$T = \frac{QW(u)}{4\pi(h_o-h)} \tag{37}$$

$$S = \frac{4uTt}{r^2} \tag{38}$$

7.3.3.2 Pumping tests: Jacob method. Cooper and Jacob (1946) developed a semilog interpretation method for the pumping test that is based on an infinite series representation for the well function. With fairly long pumping times, the solution for aquifer drawdown can be represented by the following relation (Linsley/Franzini, 1979):

$$h_o - h = \frac{2.3Q}{4\pi T} \log \frac{2.25Tt}{r^2 S} \tag{39}$$

A semilog plot of drawdown, h_0-h, versus the logarithm of time, t, results in a straight line. An extrapolation of the linear plot to the intersection with the zero drawdown axis reveals the well's time lag, referenced as t_0. Using this graphical methodology, the basic aquifer parameters can be verified from the field-measured drawdown values. Knowing the pumping rate, Q, and the measured drawdown for one log cycle, h, the values for T and S can be calculated using the relations shown as follows (Freeze and Cherry, 1979):

$$T = \frac{2.3Q}{4\pi(h_0 - n)} \tag{40}$$

$$S = \frac{2.25\ Tt_0}{r^2} \tag{41}$$

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8. IN-SITU PROCESSING/TREATMENT TECHNIQUES

8.1 General. The in-situ processing and treatment technologies discussed in this section are methods of treating lagoon contents directly, as opposed to systems such as slurry walls or cover/cap systems that isolate or contain the entire lagoon. Direct treatment techniques include biological, chemical, and physical processes used to treat the waste and thereby render it nonhazardous (or less hazardous). In-situ processing is often used in conjunction with other containment techniques.

Treatment techniques covered in this discussion include the following:

(a) Solidification/stabilization.
(b) Biological, chemical, and physical treatment.

Treatment and processing technologies considered for lagoon closure must be suitable for treating highly complex waste streams. Table 30 is a listing of compounds thought to be present in waste lagoons. Due to their reactivity, explosives are the contaminants of primary concern. However, if metals are also present they must be treated or stabilized so that the waste is no longer leachable. The U.S. EPA has established a standard testing procedure to evaluate the leachability of many wastes. This test, the EP toxicity test, can be used in reference to metal waste streams.

In general, two approaches for waste processing or treatment can be considered for in-situ lagoon closure. One approach involves the in-lagoon mixing of the treatment reagents and the waste material. The required reagents are added directly to the lagoon and, if necessary, mixed with the wastes, typically using drag line or backhoe equipment. This approach offers the advantage (and cost savings) that wastes do not have to be removed from the lagoon. A potential disadvantage is that homogenous mix and thorough treatment is more difficult to obtain.

A second approach involves out-of-lagoon treatment where wastes are removed from the lagoon and processed through a small transportable plant or reactor set up next to the lagoon. This approach involves more materials handling steps, however, a higher level of process control is possible.

The majority of the treatment processes discussed in this report will require out-of-lagoon processing. However, some of the simpler processes such as fixation or biological treatment do not require a specialized reaction vessel, so that, in some cases, in-lagoon processing may be possible.

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TABLE 30.   SUMMARY OF EXPLOSIVES AND OTHER COMPOUNDS
            IDENTIFIED IN WASTE LAGOONS

TNT
RDX
HMX
DNT
Tetryl
Mercury
Octol (RDX-70; TNT-30)
Composition A (RDX-91; Wax-9)
Composition B (RDX-60; TNT-39; Wax-1)
Propellants
Nitrocellulose
Nitroglycerine
Tritonal
Ammonia picrate
PETN
UDMH
Amitol
Aniline
Nitrobenzene
Barium nitrate
Lead azide
Lead styphnate
Acids
Ammonium nitrate
Lead
Zinc
Copper
Iron
SO_4
PO_4

It should be recognized that many treatment techniques that may be applicable to in-situ closure of lagoons are innovative technologies that at this time have not been proven through long-term application.

Some of these technologies are still in the developmental stage and process reliability has not been fully demonstrated. These innovative technologies will be discussed only in brief. The emphasis of this discussion is on standard practice or proven state-of-the-art technology.

8.2 Solidification/stabilization.

8.2.1 Process description. Waste fixation is a term that is generally used to refer to solidification/stabilization processes. These processes are normally used to isolate, immobilize, or contain sludge and semi-solid waste materials by combining a fixation agent (admixture material) with the waste. Fixation technologies usually include treatment techniques designed to process the sludge and semi-solid wastes into a solid form. Often this solid form will exhibit nonhazardous or less hazardous characteristics. Fixation technologies have evolved largely as an outgrowth of U.S. Department of Transportation regulations promulgated in the 1960's that restrict the transport of liquid radioactive wastes (Pojasek, 1979). The processes have, therefore, been in use for some time so that process reliability for some applications is fairly well demonstrated.

The terms solidification and stabilization are often used interchangeably, however, they represent different concepts. Solidification refers to the production of a solid, monolithic material with a high level of structural integrity. Stabilization refers to the immobilization of toxic/hazardous constituents by means of a chemical reaction to form insoluble compounds or by means of entrapment of the constituents in a stable, watertight lattice.

Some fixation processes have been found to be applicable to the treatment and disposal of various hazardous wastes. Use of these techniques to treat wastes, however, can be restricted due to economic considerations. Also, not all fixation processes are suitable for treating complex, nonhomogeneous wastes. Chemical compatibility between the waste and the fixation agent can be problematic. Therefore, consideration of waste constituents must be taken prior to selecting a fixation process.

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The primary goals of solidification/stabilization are as follows:

(a) To improve the handling and physical characteristics of wastes.
(b) To render hazardous products chemically nonreactive and nonhazardous.
(c) To immobilize the hazardous constituents in a waste by decreasing waste solubility.

Solidification/stabilization is achieved by mixing waste with a fixation agent that either surrounds and physically entraps the waste and hardens or chemically bonds with the waste to form a solid matrix. Ideally, the resultant product is a nonreactive monolithic mass of good structural stability, low permeability, and low solubility, which is resistant to bio-chemical degradation and weathering.

Fixation techniques can be grouped according to the nature of the fixation agent used in each process. The following techniques will be discussed in this report:

(a) Cement-based techniques.
(b) Lime-based techniques.
(c) Thermoplastic techniques.
(d) Organic polymer techniques.

Many of these fixation processes are of a proprietary nature and may be covered by various vendor patents. As a result, the exact composition of the fixation agents is not always available.

Several other fixation techniques exist that will not be covered because they are not well suited for processing lagoon wastes. One such process is encapsulation, which is used to seal wastes in containers, and thus is not suitable for treatment of bulk quantities of waste. Glassification is another example of a process that could be used to treat a wide variety of wastes. However, economic considerations often prohibit its use. This process is extremely expensive and is generally used to solidify small volumes of radioactive material.

8.2.1.1 Cement-based techniques. As the name implies, cement-based techniques use cement, commonly portland cement, as a fixation agent. Portland cement is composed of about 55 percent tricalcium silicate, 25 percent dicalcium silicate, 10 percent tricalcium aluminate, and 10 percent calcium aluminoferrite.

When water and waste are mixed with the anhydrous cement, a calcium-aluminum silicate-hydrate gel is produced that slowly hardens into a solid crystalline mass. Thus, the waste is fixed within a monolithic silicate matrix, and incorporated into the cement crystal structure.

A general cementation reaction can be expressed as follows:

$$SiO_2 + Al_2O_3 + Ca(OH_2) \longrightarrow CaO \cdot Al_2O_3 \cdot SiO_2 \cdot H_2O$$
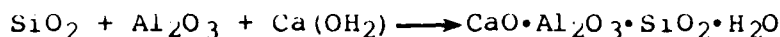
This reaction will vary, however, depending on the following:

(a) The composition of the cement used.
(b) The nature of any additives used.
(c) The nature of any impurities present in the waste.

Some wastes contain impurities that can impede the setting and curing process of solidification. The resultant product can then be nonstable or friable. For example, organics at concentrations of greater than 10 percent can interfere with solidification (Kitchens, 1980). Other impurities, including salts of zinc, copper, lead, manganese, and tin; sodium salts of arsenate, borate, phosphate, iodate, and sulfide; and sulfate salts, act as setting retarders that may significantly reduce the strength of the solidified product (EPA, 1980). Very fine particulate matter, such as fine silts and silty clays, can also weaken a cement fixed waste product, as these materials may coat the larger solids in the waste, and weaken the bond between the large waste particles and the cement (Kitchens, 1980).

The detrimental effects of some of these impurities may be overcome by the use of certain additives that have been found to enhance the cementation reaction. These additives include sulfides, asbestos, latex, plastics, clay, bentonite, silicates, lime, and other proprietary compounds (EPA 1980).

Because the cementation process can be affected by various waste constituents and additives, it is necessary to perform a comprehensive chemical analysis of a waste and conduct bench-scale testing prior to solidification treatment. Waste characterization data are required to estimate the optimum mix of cement, waste, and additives for processing. A bench-scale testing program designed to simulate the fixation process can then

be conducted using the actual waste material and estimated proportions of the fixation agent. The bench-scale tests are used for the following reasons:

(a) Confirm that the cementation process will work and that the mixture cure will have acceptable structural properties.

(b) "Fine tune" the proportions of the fixation agent to achieve acceptable product characteristics.

The advantages and disadvantages of using cement-based fixation for the in-situ treatment of lagoon wastes are presented in Table 28.

8.2.1.2 Lime-based, pozzolanic processes (not containing cement). Lime-based processes are very similar to cement-based fixation techniques with the exception that fine-grained silicious pozzolanic material and lime are used as solidifying agents instead of cement. The reaction chemistry is quite similar. Pozzolanic materials such as fly ash, blast-furnace slag, and cement-kiln dust, when combined with lime and water, form a concrete-like solid sometimes referred to as pozzolanic-crete. Fly ash, for example, has a chemical composition of 30-50 percent silicon dioxide, 14-30 percent aluminum oxide, 10-30 percent iron oxide, and 1.5-4.5 percent calcium oxide (Kitchens, 1980). When fly ash is mixed with lime and water, the mixture has the same stoichiometry as portland cement and behaves like cement when mixed with wastes. Other pozzolanic materials react similarly to the cementation process.

The implementation of pozzolanic processes would require a detailed knowledge of the waste composition and bench-scale testing for verification purposes. This would be conducted in a similar manner as that discussed for the cement-based techniques. However, because the composition of the pozzolanic materials will vary according to the source, it would be necessary to obtain actual samples from the pozzolanic source for the bench-scale testing.

The main advantage of pozzolanic fixation is that it is generally inexpensive. The pozzolanic materials used in the process are "waste" products that may be easily obtained at low cost if a source of these materials is located close to the site. Also, the chemistry of lime/pozzolanic reactions is well known and tested. Other advantages and disadvantages of lime-based solidification processes are the same as these for cement-based techniques, shown in Table 31.

TABLE 31. SUMMARY EVALUATION OF CEMENT-BASED FIXATION

Advantages

1. Treatment is relatively inexpensive. Cement is plentiful and moderately priced.

2. Cement mixing equipment and technology is commonplace. Specialized labor is not required.

3. Cement-based solidification processes are fairly tolerant of variations in sludge/waste moisture content. Sludges with moisture contents ranging from 25-60 percent can be solidified.

4. The strength and permeability of the final product can be varied according to the amount of cement added.

5. The system is very effective for immobilizing heavy metals. Cement is naturally alkaline, and, at high pH, most multivalent cations, including heavy metals, are converted to carbonates or insoluble hydroxides. Thus, metal ions are incorporated into the crystal structure of cement and are resistant to water leaching.

6. Cement-based solidification technologies are well developed and proven through many applications in the hazardous and industrial waste disposal fields.

7. In-lagoon or out-of-lagoon processing is possible.

Disadvantages

1. The process is not suitable for wastes with organic content greater than approximately 10 percent.

2. Certain impurities in waste can adversely affect the setting or curing of the waste/concrete mixture, making some wastes, particularly those with a high salt content, unsuitable for cement-based treatment.

3. Unless properly protected, some solidified products are susceptible to decrepitation by weathering.

4. Solidified products can be susceptible to leaching by mildly acidic solutions.

5. The volume of the final product produced by cement-based treatment can be double that of products of other solidification processes.

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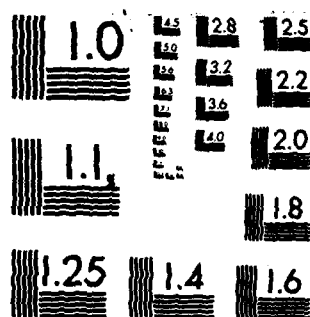CHESTER PA M F COIA ET AL. JAN 84 DRXTH-TE-CR-83224
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8.2.1.3 Thermoplastic techniques. Thermoplastic fixation involves the use of thermoplastic materials to coat and encapsulate waste in a solid matrix. Thermoplastics can be described most easily as materials whose behavior when heated is analogous to that of paraffin. At temperatures greater than 130-230°C, they are liquids; when cooled to lower temperatures, they become solids. Thermoplastics can be liquified and solidified repeatedly without the loss of these thermoplastic properties. Common fixation agents that can be classified as thermoplastics include paraffin, asphalt, polyethylene, and nylon.

Thermoplastic fixation is accomplished by mixing and heating wastes with a thermoplastic material in a specialized piece of equipment known as an extruder. The extruder serves the dual purpose of reducing the particle size of the wastes while mixing and thoroughly coating the waste particles with thermoplastic material. The temperature profile along the mixing screws of the extruder can be closely controlled. While passing through the hot mixing screws, water and volatile organics are evaporated and collected in a condenser system. Thermoplastic material is then mixed into the solid waste particles. After passing through the extruder, the coated waste material cools and solidifies. The process generally results in a product of substantially reduced volume, due to water loss, and a product that is extremely resistant to leaching, weathering, and biodegradation.

Care must be taken when selecting a thermoplastic fixation material so that it is compatible with the waste being treated. Thermoplastics are generally compatible with most wastes, with the exception that some organic chemicals act as solvents towards organic thermoplastics. Asphalt or asphalt bitumen has been found to be one of the most versatile thermoplastic materials (EPA, 1979).

The advantages and disadvantages of thermoplastic-based fixation are shown in Table 32.

8.2.1.4 Organic polymer techniques. Organic polymer-based fixation involves entrapping wastes in a polymer matrix in a multistep process. The waste is first thoroughly mixed with an organic monomer. Catalyst is then added to the mixture which causes the monomer to polymerize. As polymerization takes place, solid waste particles are trapped within the polymer matrix, while some of the liquid escapes. The polymer-waste matrix is then placed in containers for disposal.

TABLE 32. SUMMARY EVALUATION OF THERMOPLASTIC
TECHNIQUES

Advantages

1. The process is suitable for treating a wide variety of wastes.

2. Processed wastes are very stable. They are resistant to acidic leaching, weathering, and microbial degradation.

3. The leachate quality of processed wastes is generally better than that observed with cement-based and lime-based systems.

4. Treatment is a highly controlled process, which allows for regulated product formation.

5. If the waste has a high moisture content, significant volume reduction of the waste is accomplished due to loss of a high percentage of the liquid content of the waste.

6. The destruction of some organic constituents may occur during the heating process.

Disadvantages

1. Expensive, highly-specialized equipment is required.

2. Skilled laborers are required.

3. Some wastes may volatilize when heated to high temperatures, thereby causing air pollution unless properly controlled.

4. The stability of explosive/reactive materials at the high extrusion temperatures would have to be determined.

5. Some organic wastes are not compatible with some thermoplastics.

6. Thermoplastics are flammable at very high temperatures; heating must be closely controlled.

7. The thermoplastic materials are generally more expensive as compared to cement-based and pozzolanic-based agents.

8. Out-of-lagoon processing would be required and would involve a higher cost as compared to in-lagoon mixing; in-lagoon mixing could not be performed.

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Organic polymer fixation techniques for hazardous waste disposal are still in the experimental/developmental stage. Urea-formaldehyde processing has been used in the past but is not highly recommended for long-term containment because it is susceptible to biodegradation (Kitchens, 1980). The urea-formaldehyde process is used mainly to make wastes easy to transport and is not intended as a permanent treatment process.

The possible use of other polymers, including polyesters, polystyrenes, and polyvinyl compounds to achieve long-term containment, is now being investigated.

The principal advantages and disadvantages of organic polymer processes are shown in Table 33.

8.2.2   Environmental considerations and constraints.

8.2.2.1   Waste and material characteristics.   Several key issues relating to the viability of waste fixation and waste and material characteristics include the following:

(a)   Compatibility of waste and fixation agent.
(b)   Waste composition and moisture content.
(c)   Variability of waste characteristics.
(d)   Bench-scale testing for delisting.
(e)   Physical   characteristics of waste and fixation agent
      to
      establish materials-handling requirements.

One of the more important factors for consideration in selecting a fixation process is the compatibility of the waste with the fixation agent. Detailed chemical analyses must be performed to determine waste characteristics prior to selecting a fixation process. Constituents of primary concern include organics, heavy metals, sulfates, and halides. Waste pH and moisture content should also be determined.

Due to the nature of waste lagoons, it is likely that the moisture content, composition, and characteristics of the waste material will vary with depth and areal location in the lagoon. Waste characterization will require a comprehensive sampling program so that the variability in waste composition (if any) can be accurately determined. If the fixation process is particularly sensitive to waste composition, this will be an important factor in determining the acceptability of a particular fixation process.

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TABLE 33. SUMMARY EVALUATION OF ORGANIC POLYMER TECHNIQUES

Advantages

1. A comparatively small amount of fixation agent is required for processing.

Disadvantages

1. This technology is generally in the experimental/developmental stages and cannot be considered proven.

2. Little is known about the compatibility of wastes with polymers.

3. Some polymers are biodegradable.

4. The long-term integrity/stability of the process is questionable. No chemical reactions occur between the waste and the polymer in the fixation process. Thus, the wastes are not chemically bound to the polymer, they are simply enclosed in the polymer matrix. If the polymer matrix is destroyed through biodegradation or weakening, the toxic wastes can be released.

5. Some of the catalysts used in the process are highly acidic and can increase the solubility of the toxic waste. If fixation takes place slowly, leaching of toxics can occur.

6. Some catalysts are explosive. The fixation process must be carefully controlled.

7. Polymerization reactions often release harmful fumes.

8. In-lagoon mixture could not be performed; out-of-lagoon processing would be required and would involve a higher cost as compared to in-lagoon mixing.

Table 34 summarizes general guidelines regarding waste compatibilities with fixation techniques. More specific guidelines cannot be presented since compatibility ultimately depends on the exact nature of the fixation agent. The exact composition of fixation agents is usually proprietary information that varies with individual vendor processes, depending on the additives used. Therefore, compatibility must be evaluated on a case-by-case basis, after referring to the general guidelines outlined in Table 34.

The physical and chemical properties of the waste and fixing agent must also be evaluated in regard to materials handling considerations. For example, if in-lagoon mixing of the waste and fixation agent is being considered, the viscosity and moisture content of the waste will be important factors in determining mixing protocol. If out-of-lagoon mixing is being considered, then the technique for removing the waste from the lagoon will require certain data. Again, moisture content and viscosity will be important along with corrosivity and solids content if pumping is being considered. For pumping, it may be necessary to add water to the lagoon contents. The characteristics of the fixing agent may also become a factor with respect to materials handling and should be assessed with respect to the following:

(a) Dust control requirements during mixing.
(b) Pre-blending of additives.
(c) Onsite bulk storage and the potential for excessive moisture addition from precipitation.
(d) Materials conveyance requirements.
(e) Variability (if any) in the composition of the fixing agent.

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TABLE 34. COMPATIBILITY OF SELECTED WASTE CATEGORIES WITH DIFFERENT WASTE FIXATION TECHNIQUES

Waste component	Treatment type			
	Cement based	Lime based	Thermo-plastic fixation	Organic polymer (UF)[a]
Organics				
Organic solvents and oils	Many impede setting, may escape as vapor	Many impede setting, may escape as vapor	Organics may vaporize on heating	May retard set of polymers
Solid organics (e.g., plastics, resins, tars)	Good -- often increases durability	Good -- often increases durability	Possible use as binding agent	May retard set of polymers
Inorganics				
Acid wastes	Cement will neutralize acids	Compatible	Can be neutralized before incorporation	Compatible
Oxidizers	Compatible	Compatible	May cause matrix breakdown, fire	May cause matrix breakdown
Sulfates	May retard setting and cause spalling unless special cement is used	Compatible	May dehydrate and rehydrate causing splitting	Compatible
Halides	Easily leached from cement, may retard setting	May retard set, most are easily leached	May dehydrate	Compatible
Heavy metals	Compatible	Compatible	Compatible	Acid pH solubilizes metal hydroxides
Radioactive materials	Compatible	Compatible	Compatible	Compatible

[a]Urea-formaldehyde resin.

Source: EPA, 1980.

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If one of the primary objectives of waste fixation is to render the waste material nonreactive or nonhazardous, then the importance of waste analysis and bench-scale testing cannot be overlooked. The bench-scale testing program can be used to produce processed samples of the waste material, which can then be tested for reactive and hazardous characteristics to determine if the desired results will be achieved. The results of these analyses could be used for delisting purposes if the waste is a listed hazardous waste. Delisting of the waste would be highly attractive in reducing regulatory and permitting requirements for lagoon closure.

8.2.2.2 Site considerations and suitability. Site conditions that may affect the viability of waste fixation and major considerations include the following:

(a)   Site environmental conditions that may affect the long-
      term integrity and stability of the fixed material.
(b)   Engineered containment and isolation techniques.
(c)   Weather conditions and material decrepitation.
(d)   Subsurface and water table conditions.

The suitability of fixation processing for in-situ lagoon closure is largely dependent on the physical and chemical stability of the treated waste and degree of treatment achieved. Ideally, fixation renders wastes nonreactive, nonhazardous, non-leachable, and stable over long periods and under severe weather conditions. If these goals can be achieved, the surrounding lagoon environments will have little or no impact on waste treatment and lagoon closure. If ideal treatment is not achieved, however, and the stability of the treated waste is questionable, environmental conditions become important.

A solidified waste should be placed in an environment where the physical and chemical integrity of the waste can be maintained. Favorable environmental conditions include the following:

(a)   Neutral pH.
(b)   Relatively dry environment.
(c)   Moderate temperatures with no deep freeze/thaw action.

Engineered containment and isolation techniques can be applied to create a more favorable environment for the ultimate disposal of fixed wastes, if such an environment is not available. These techniques can include cover/cap systems, berms and dikes, and groundwater diversion, which are discussed in other sections of this report.

The curing and solidification characteristics of the waste-fixing agent mixture must be compared to expected weather conditions. If curing/solidification is adversely affected by excessive moisture (e.g., precipitation), freeze/thaw conditions, or high temperature and excessively dry conditions, then special controls and protection may be required. This should be assessed as part of the bench-scale testing program. In general, the cement-based and pozzolanic techniques should not be adversely affected by normal weather conditions during curing.

In addition to weather conditions, the subsurface and groundwater characteristics of a particular site must be evaluated for compatibility with the fixation process. For example, high water table conditions may result in saturation of the sludge in the bottom of the basin, thereby causing excessive moisture. This condition would make moisture content very difficult to control during the fixation process and may result in poor long-term stability if the fixation mixture is returned to the same lagoon.

8.2.2.3 Other considerations. Out-of-lagoon processing of lagoon wastes may be accomplished by setting up transportable treatment equipment at the lagoon site. A typical scenario for treatment is shown on Figure 61. Waste is first pumped or otherwise excavated from the lagoon to a holding/processing area. The sludge is then thoroughly mixed through the processing equipment. Within the processing system, the sludge is mixed with the fixing agent. Following processing, the fixed sludge is returned to the lagoon or disposal area for curing, solidification, and ultimate disposal. Sampling and process control would be utilized to ensure acceptable final product quality. Closer process control and a more homogenous mix can generally be achieved with an out-of-lagoon system.

Safety is an issue of primary concern for fixation processing. For example, in the scenario just discussed, remote sensing techniques would be required to scan for unexploded ordnance prior to disturbing the lagoon sediments. A coarse bar screen should be used on the intake end of the pump to prevent any undetected ordnance from entering the pump and treatment system, and all equipment should be operated via remote control.
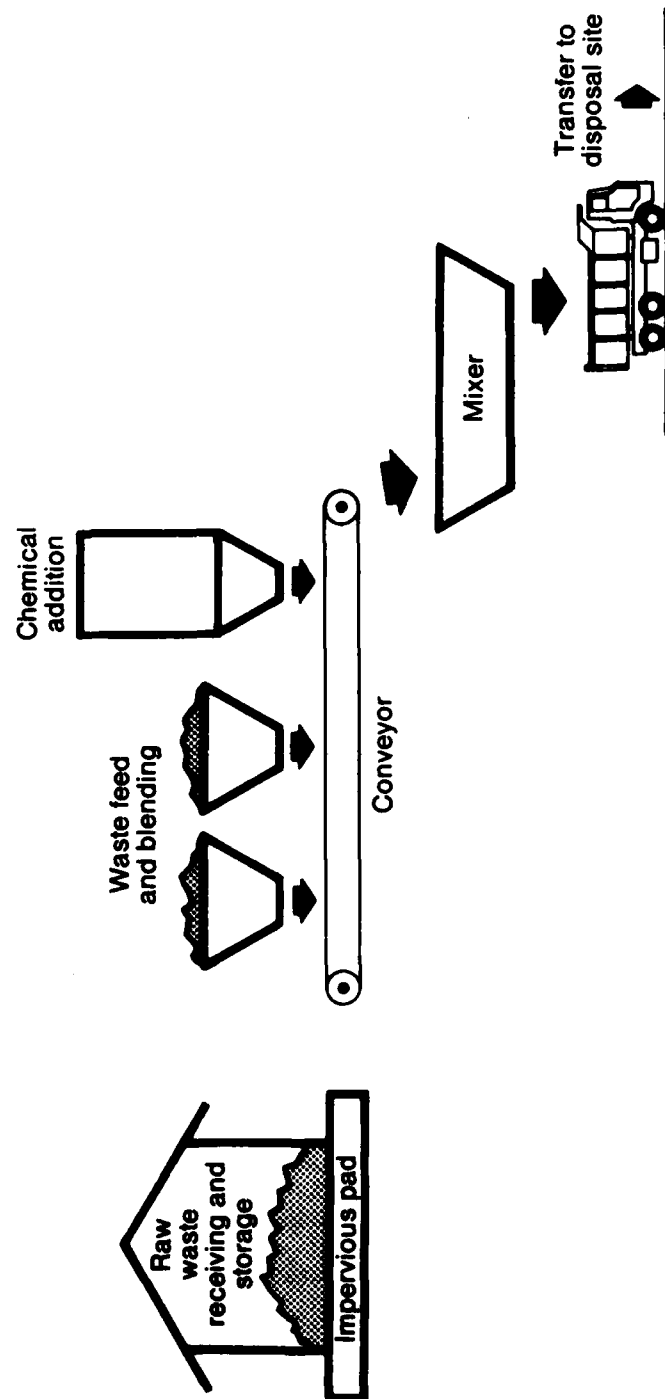
Figure 61.   Waste fixation process flow diagram.

In cases where high concentrations of TNT and other explosives are present in the waste, some fixation processes may not be applicable to lagoon treatment. Certain processes may subject wastes to high shear and high temperatures that could possibly cause detonation. Little information is currently available on the behavior of reactive wastes under fixation processing plant conditions. Research in this area is recommended to determine precise safety and handling requirements for possible lagoon treatment.

8.2.3 Process evaluation methodology. Fixation technologies are evaluated primarily on the basis of three factors: compatibility of the waste with fixation agents, results of bench-scale tests, and economic considerations.

8.2.3.1 Waste compatibility. Once the chemical composition of the waste requiring treatment has been determined, a preliminary evaluation is made regarding waste compatibility with the various fixation processes. Processes that appear to be suitable for achieving the desired technical objectives (e.g., delisting, solidification) of waste treatment are recommended for bench-scale laboratory testing.

Bench-test results -- Due to the propietary nature of many fixation processing techniques, bench-scale tests are usually performed by process vendors. Waste samples can be sent to the vendor for processing, and treated samples will be returned for further evaluation. Treated waste samples can be evaluated with respect to the degree of treatment achieved. A determination must be made as to whether or not the waste can be classified as nonhazardous. If a nonhazardous classification is determined, the physical integrity and durability of the waste should be determined.

The hazardous or nonhazardous classification is dependent on the following four waste characteristics:

(a)   Ignitability.
(b)   Corrosivity.
(c)   Reactivity.
(d)   EP toxicity.

With the exception of reactivity, standard EPA protocols for hazardous waste determination should be used for these sample analyses. The reactivity test protocol may include the five-tier or eight-tier tests now being evaluated by USATHAMA.

At present no approved reactivity protocol exists. However, the Army five-tier protocol can be used to develop safety data, and regulatory agencies may accept these data.

A determination of the physical integrity and durability of the waste must be made to evaluate the long-term effectiveness of treatment. No standard EPA protocols exist for this type of determination. In lieu of better methods, some geotechnical physical property tests have been used to evaluate product stability. Suggested standard tests are shown in Table 35.

Economic considerations -- The total cost of fixation treatment is mainly dependent on the following:

(a) Costs for laboratory testing.
(b) Equipment costs.
(c) Materials costs for solidification agents and additives.
(d) Labor costs.
(e) Costs for energy usage.
(f) Fees for royalties for use of patented treatment processes.

In general, the in-situ approach to fixation processing, when applicable, will be less costly than out-of-lagoon processing due to less material handling steps. In addition, the pozzolanic techniques may offer a cost savings compared to cement-based techniques if a suitable source of pozzolanic material is located nearby.

The results of the bench-scale tests are used not only to verify the performance of the fixation process but also to determine the proportions and quantity of fixation additives. This information can then be used to estimate purchase and delivery costs for the fixation agents.

The relative costs for various solidification processes are presented in Table 36. When assessing the overall total costs for waste fixation and lagoon closure, one must consider the additional engineering controls which would have to be included to complete closure. These controls could include a final cover/cap system, berms or dikes, and groundwater controls.

8.2.4 Environmental performance verification.

8.2.4.1 Quality assurance. The primary responsibility of the quality control officer during in-situ fixation processing is to determine that all prespecified treatment requirements are met.

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TABLE 35. SUGGESTED GEOTECHNICAL PHYSICAL PROPERTY TESTS

Parameter	Test
Unconfined compressive strength	ASTM Method D2166-66
Wet/dry durability	ASTM Method D559-57
Freeze/thaw durability	ASTM Method D560-57 (EPA 1980)

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TABLE 36. PRESENT AND PROJECTED ECONOMIC CONSIDERATIONS FOR WASTE STABILIZATION/SOLIDIFICATION SYSTEMS

Type of treatment system	Major materials required	Unit cost of material	Amount of material required to treat 100 lb of raw waste	Cost of material required to treat 100 lb of raw waste	Trends in price	Equipment costs	Energy use
Cement-based	Portland cement	$0.03/lb	100 lb	$ 3.00	Stable	Low	Low
Pozzolanic	Lime fly ash	$0.03/lb	100 lb	$ 3.00	Stable	Low	Low
Thermoplastic (bitumen-based)	Bitumen drums	$0.05/lb $27/drum	100 lb 0.8 drum	$18.60	Bitumen prices are rising rapidly because of oil prices	Very high	High
Organic polymer (polyester system)	Polyester catalyst	$0.45/lb $1.11/lb $17/drum	43 lb of polyester-catalyst mix	$27.70	Price could rise rapidly due to oil shortage	Very high	High

In general, the quality assurance officer must monitor the following potential variables to ensure that they are within the acceptable ranges:

(a) Sludge characteristics such as moisture content and viscosity (grab samples).

(b) Composition of fixing agents such as free lime content (grab samples).

(c) Sludge mixing or blending to achieve homogeneity (if needed).

(d) Mixing and blending of fixation agents (if necessary).

The quality control officer must also ensure that the predetermined proper ratio of waste to fixation agent and additives are used in processing, and for processes that are temperature or moisture sensitive, these variables must be precisely controlled. Grab samples of the waste-fixation agent mixture should be collected frequently during the treatment process. Some of these samples can be used initially for physical property testing (e.g., seven-day testing) while some samples should be kept on the site to be used for long-term (e.g., 28 days or longer) performance verification. The testing of these mixture samples can include those same tests used during the bench-scale testing, as discussed in subsection 8.2.3.1.

8.2.4.2 Long-term performance verification. After it is placed in its final disposal location, the fixed waste product should be disturbed as little as possible in order to preserve its physical integrity and not disrupt the curing process. Therefore, any destructive-type test methods are discouraged for long-term performance verification. Alternatively, nondestructive or remote methods are recommended. Suggested test methods include the following:

(a) Visual inspection.

(b) Groundwater monitoring.

(c) Leach testing.[69]

(d) Physical property testing of grab samples collected during processing.

8.2.5 Application to lagoon waste treatment. Solidification/stabilization is one of the few treatment processes that is generally suitable for treating complex wastes. Most lagoon wastes have been found to contain high concentrations of both heavy metals and organic explosives. This combination of contaminants tends to be problematic for most conventional solid waste

treatment systems. Systems designed to treat organics have little effect on inert metals, while treatment systems designed for metals removal usually do not remove organics. Solidification, however, may be effective for treating both organics and inorganic wastes.

Of the fixation processes discussed in this report, cement-based, lime-based (pozzolanic), and thermoplastic techniques appear to have the highest potential for effectively treating the lagoon wastes. In preliminary testing on lagoon sediments with a higher organic content, thermoplastic processing has been superior to other fixation methods for achieving stabilization of the waste. The leachate quality of processed wastes is better than that observed with other fixation processes (Triegel, 1983). The advantages and disadvantages of thermoplastic solidification for lagoon treatment are presented in Table 32.

Thermoplastic solidification appears to be a viable option for in-situ lagoon treatment, therefore, further research and development in this area is recommended.

Research is also recommended to characterize the explosivity of lagoon wastes with respect to TNT concentration. Sludge handling guidelines must be established so that lagoon wastes can be processed and treated in a safe manner.

Where "stabilization" is the major objective, the cement and lime-based techniques would be more applicable to those lagoons containing waste with a low organic content. For strictly solidification, these techniques could be applied to wastes with higher organic content.

The cement- and lime-based techniques offer a potential cost savings as compared to the thermoplastic method. Further research and development of the cement- and lime-based techniques is recommended to more closely define the acceptable ranges in waste composition and characteristics as it relates to product characteristics (e.g., leachability, strength, etc.).

8.3 <u>Chemical, biological and physical treatment.</u> Several companies are currently under contract to USATHAMA to identify chemical, biological, and physical methods of treating explosive wastes. The processes evaluated in these preliminary studies that may have applicability for in-situ lagoon treatment and closure are addressed briefly in the subsections that follow. These processes could be used to improve the characteristics of the waste prior to in-situ closure. A waste could be rendered nonreactive or nonleachable prior to in-situ closure, which would be beneficial from a regulatory approval and environmental standpoint.

8.3.1 Chemical treatment. Chemical treatment processes that have been identified as potentially suitable for treating explosive wastes include the following (Benecke et al., 1983):

(a) Sulfur-based reduction.
(b) Sodium borohydride reduction.
(c) Base-initiated decomposition.
(d) Reductive cleavage.
(e) Chemically-initiated free radical treatment.

Each process is summarized in the subsections that follow.

8.3.1.1 Sulfur-based reduction. The explosive contaminants commonly found in lagoon wastes are all organic compounds with one or more nitro groups $(R-NO_2)$. Their structures are illustrated on Figure 62.

Sulfur-based reducing agents, including sodium sulfide, sodium bisulfide, and sodium metabisulfide, can be used to reduce the nitro groups on these explosives to amino groups $(R-NH_2)$, yielding nonexplosive amino compounds (Benecke et al., 1983). The reaction chemistry is shown on Figure 63.

When treated as just described, some explosives yield completely innocuous compounds. Nitroglycerine and nitrocellulose, for example, yield glycerol and cellulose, respectively. TNT, DNT, and tetryl, on the other hand, yield aromatic amines $(R-CN; R-NH)$ which are nonexplosive, but toxic compounds (Benecke et al., 1983).

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NC:

NGu: $NH_2C-NHNO_2$ with $\overset{NH}{\underset{\parallel}{}}$

Tetryl:

Lead styphnate:

2, 4-DNT:

2, 6-DNT:

TNT:

RDX:

HMX:

NG:
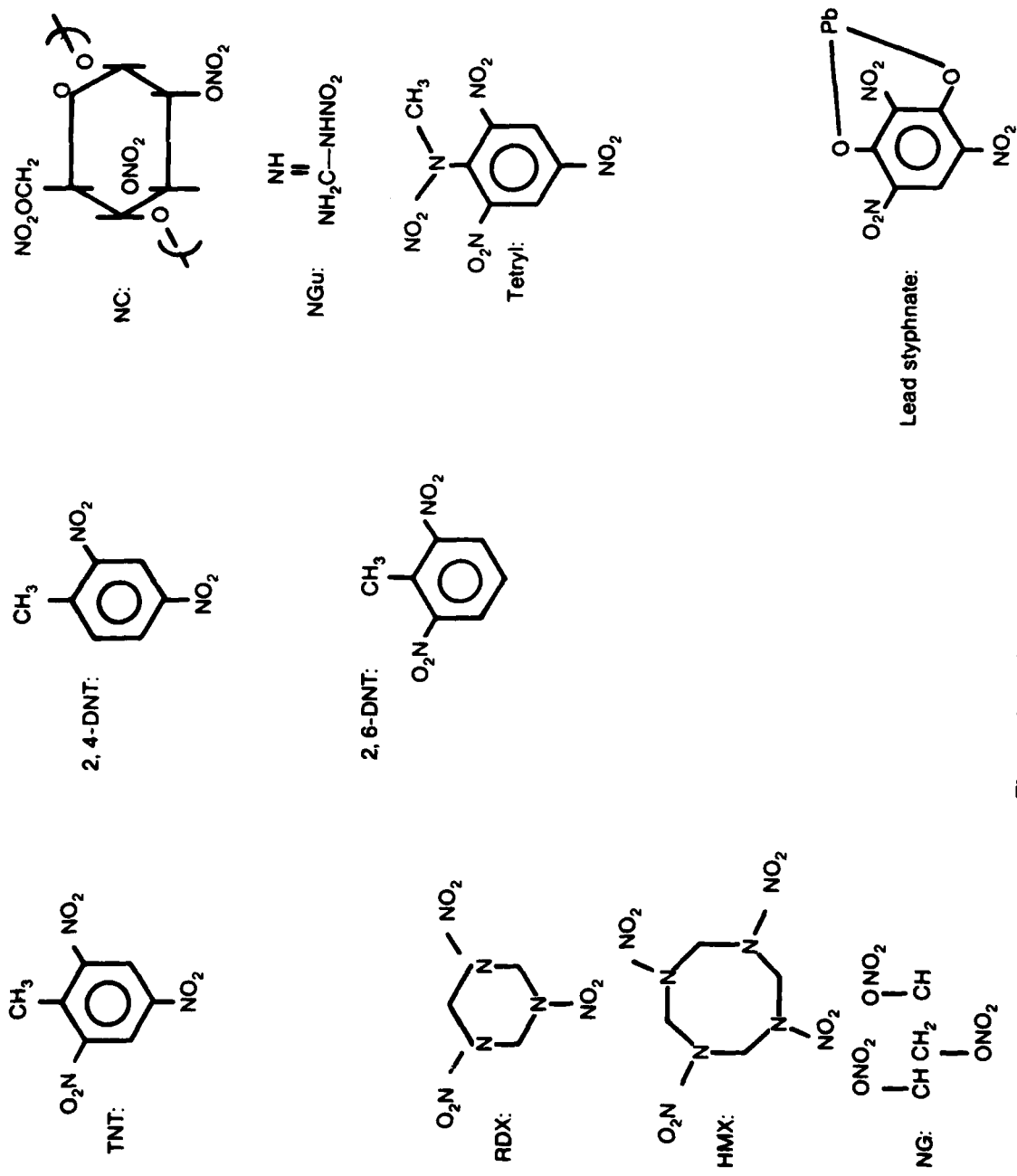
Figure 62. Structures of explosives.

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NG $\xrightarrow[\text{Na}_2\text{S}]{\text{NaHs}}$ Glycerol + NH$_3$

NC $\xrightarrow[\text{Na}_2\text{S}]{\text{NaHs}}$ Cellulose + NO$_x$ + H$_2$S + NO$_2$

TNT $\xrightarrow{\text{Na}_2\text{S}}$ (2,4,6-triaminotoluene structure: CH$_3$, NH$_2$, NH$_2$, NH$_2$)

RDX, HMX $\xrightarrow[\text{Na}_2\text{S}_2\text{O}_3]{\text{Na}_2\text{S or}}$ $-$N$-$NH$_2$

Tetryl $\xrightarrow[\text{Na}_2\text{S}_2\text{O}_3]{\text{Na}_2\text{S or}}$ Nonexplosive, Water soluble products

NG $\xrightarrow[\text{ph11}]{\text{Na}_2\text{S}}$ NH$_2$ $-$ C $-$ NHNH$_2$ (C double bonded to NH)
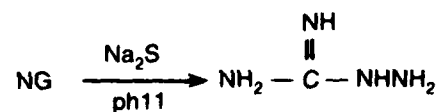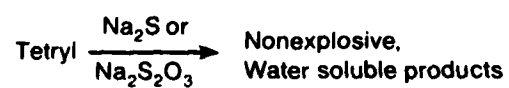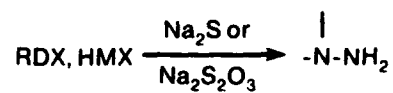
Source: Benecke et al., 1983

Figure 63. Sulfur-based reduction of explosives.

While sulfur-based reduction can be a useful technique to treat some pure explosives, its use for lagoon treatment may be limited due to the complex and sometimes heterogeneous nature of lagoon wastes. Toxic amines are formed from the reduction of TNT, other nitro aromatics, and nitramines explosives; the reaction products and by-products of other lagoon compounds are largely unknown. Therefore, the process will have limited applicability for final lagoon treatment and closure.

The advantages and disadvantages of sulfur-based reduction of lagoon sediments are outlined in Table 37.

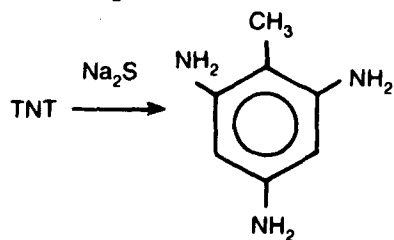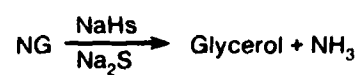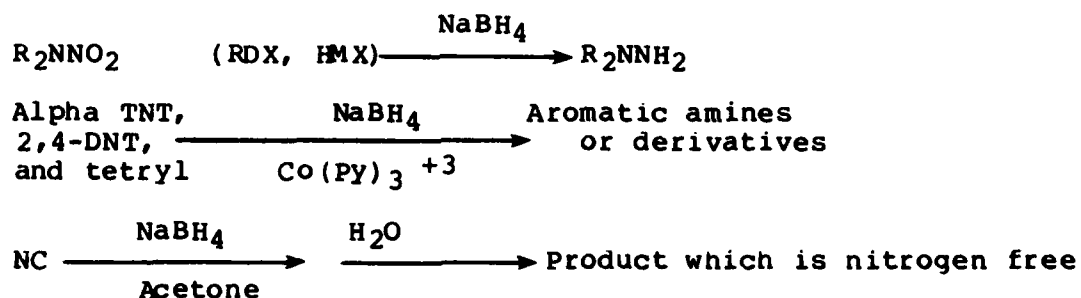8.3.1.2 Sodium borohydride reduction. Aqueous solutions of sodium borohydride may be used with a cobalt catalyst to reduce explosives to nonexplosive compounds. RDX, HMX, and nitroguaridine are reduced to hydrazines. TNT, 2,4 DNT, and tetryl are reduced to aromatic amines or derivatives, and nitrocellulose and nitroglycerine will yield nitrogen-tree products (Benecke et al., 1983). The chemical reactions are shown as follows:

$$R_2NNO_2 \quad (RDX, HMX) \xrightarrow{\text{NaBH}_4} R_2NNH_2$$

$$\begin{array}{l} \text{Alpha TNT,} \\ \text{2,4-DNT,} \\ \text{and tetryl} \end{array} \xrightarrow[\text{Co(Py)}_3 {}^{+3}]{\text{NaBH}_4} \begin{array}{l} \text{Aromatic amines} \\ \text{or derivatives} \end{array}$$

$$NC \xrightarrow[\text{Acetone}]{\text{NaBH}_4} \xrightarrow{\text{H}_2\text{O}} \text{Product which is nitrogen free}$$

Source: Benecke et al., 1983.

Sodium borohydride treatment is thought to have about the same degree of applicability to lagoon treatment and closure as does sulfur-based reduction treatment. The two treatment processes yield very similar results. The advantages and disadvantages of sodium borohydride treatment are shown in Table 38.

TABLE 37. SUMMARY EVALUATION OF SULFUR-BASED REDUCTION
TREATMENT OF LAGOON SEDIMENTS

Advantages

1. All explosives of concern are reduced to nonexplosive compounds.

2. Nitrate ester explosives (e.g., nitroglycerine and nitrocellulose) yield nontoxic products.

3. Reduction reactions are very rapid and nearly quantitative.

4. Treatment reagents are inexpensive.

Disadvantages

1. Toxic (but nonexplosive) products are formed from nitro aromatic and nitramine explosives; e.g., TNT, tetryl, DNT are reduced to aromatic amines and mixed nitro amines; and RDX and HMX are reduced to hydrazines.

2. By-products formed from nonexplosive lagoon constituents are unknown.

3. Sulfur-based reductants and their reaction products give off noxious odors.

TABLE 38.   SUMMARY EVALUATION OF SODIUM BOROHYDRIDE TREATMENT
OF LAGOON SEDIMENTS

Advantages

1.   Most explosives are reduced to nonexplosive compounds.

2.   Sodium borohydride treatment does not produce the noxious sulfur gases that are reaction products of sulfur-based reductions.

Disadvantages

1.   Toxic aromatic amines may be produced by the reduction of nitro aromatic explosives, such as TNT, DNT, and tetryl.

2.   Toxic hydrazines are produced from the reduction of RDX and HMX.

3.   The cobalt salt catalyst required for the reaction may be considered a hazardous material and, therefore, requires proper disposal.

4.   Sodium borohydride will slowly hydrolyze in water. Therefore, significant amounts of reagents may be required for treatment.

8.3.1.3 Base-initiated decomposition. A wide range of explosives can be effectively decomposed when treated with strong basic solutions (Benecke et al., 1983). Reaction products are nonexplosive and mainly nontoxic, however, some toxic compounds are produced. Typical reactions are shown as follows:

$$RDX, HMX \xrightarrow{OH^-} CH_2O, N_2O, NH_3, N_2, HCO_2^-$$

$$NG \xrightarrow{OH^-} CH_3CO_2^-, HCO_2^-, NO_3^-, NO_2^-$$

$$NC \xrightarrow{OH^-} \text{organic acids}, NO_3^-, NO_2^-, NO_x^-, CO_x, \text{cyanides}$$

$$NGu \xrightarrow{OH^-} N_2O, CO_2, NH_3$$
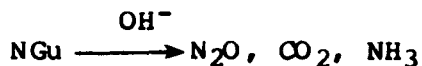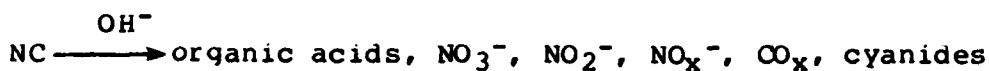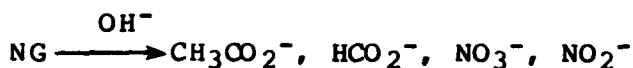
Source: Benecke et al., 1983.

The principal advantages and disadvantages of treatment of lagoon wastes with basic solutions are listed in Table 39.

8.3.1.4 Reductive cleavage. Nitrate esters and nitramine explosives are known to undergo a reductive cleavage of nitro groups in the presence of zinc dust and an organic solvent. The resulting products are nonexplosive and possibly nontoxic compounds (Benecke et al., 1983). The postulated reaction chemistry is shown as follows:

Nitrate esters

$$(NG)\ RONO_2 \xrightarrow{Zn} RO^- + Zn^{+2} + NO_2^-$$

Nitramines

$$(RDX, HMX)\text{-N-}NO_2 \xrightarrow{Zn} \text{-N}^- + Zn^{+2} + NO_2^-$$
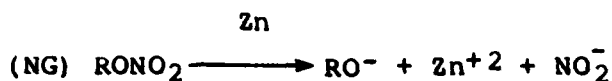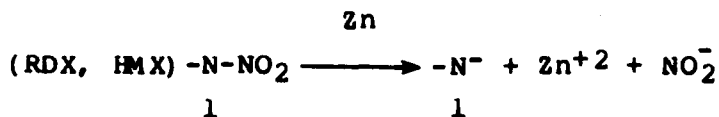
Source: Benecke et al., 1983.

TABLE 39. SUMMARY EVALUATION OF BASE-INITIATED TREATMENT
OF LAGOON SEDIMENTS

Advantages

1. Decomposition reactions are relatively rapid and effective.

Disadvantages

1. Some toxic products are produced.

2. The highly basic solutions required for the reaction will require special safety and handling procedures.

3. When present, heavy metals may be leached from lagoon wastes by strong basic solutions.

4. The reaction is not controllable for wastes with high TNT concentrations. Explosion may result.

The advantages and disadvantages of reduction cleavage chemical treatment are outlined in Table 40.
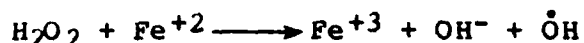
8.3.1.5 Chemically-initiated free radical treatment. Certain explosives are known to decompose when attacked by hydroxyl tree radicals (Andrews, 1980). Chemically initiated free radical treatment is a possible treatment scheme conceptualized by Battelle (Benecke et al., 1983) in which chemically-generated hydroxyl radicals are predicted to initiate the decomposition of explosives. Hydroxyl radicals can be readily generated by Fenton's reagent, which is a solution of ferrous salts in aqueous hydrogen peroxide. Free radicals generated from Fenton's reagent are predicted to decompose explosives completely to CO_2 and ammonia. The postulated reaction is as follows:

Fenton's reagent

$$H_2O_2 + Fe^{+2} \longrightarrow Fe^{+3} + OH^- + \overset{.}{O}H$$

$$OH + RDX, \ HMX, \ TNT, \ DNT \longrightarrow Unstable \ intermediates \longrightarrow Small,$$
$$gaseous \ compounds$$

Source: Benecke et al., 1983.

The potential advantages and disadvantages of chemically-initiated free radical treatment are shown in Table 41.

8.3.1.6 Applicability of chemical treatment to lagoon closure. The chemical treatment processes briefly described in the previous subsections all have the potential applicability for desensitization of explosive wastes. These processes are effective for desensitizing explosives to nonexplosive, but not necessarily nonhazardous or nontoxic forms.

The use of these processes in lagoon closure plans is, therefore, somewhat limited since the ultimate goal of waste treatment in lagoon closure is to render wastes not only nonexplosive, but also nonhazardous.

Pretreatment applications for chemical treatment, however, are feasible. Chemical treatment can be utilized to pretreat and desensitize lagoon wastes prior to further processing. The explosive nature of untreated lagoon wastes limits the number of viable alternatives for in-situ closure of lagoons containing explosive wastes. If desensitization of lagoon wastes can be accomplished through chemical pretreatment, various engineering alternatives can be considered for in-situ closure plans that previously would have to be eliminated due to potential hazards involved with handling and treating explosive wastes. Therefore,

TABLE 40. SUMMARY EVALUATION OF LAGOON SEDIMENT TREATMENT BY
REDUCTION CLEAVAGE

Advantages

1. Nonexplosive products are produced from some explosives.

Disadvantages

1. Treatment must be contained in a closed system to recover hazardous organic solvents used in the reaction.

2. The applicability of the reaction to nitro aromatics such as TNT, DNT, and tetryl is not known.

3. Some reaction products may be toxic.

TABLE 41. SUMMARY EVALUATION OF CHEMICALLY-INITIATED FREE
RADICAL TREATMENT OF LAGOON WASTES

Advantages

1. A relatively high concentration of reactive free radicals can be produced.

2. Complete explosives destruction to CO_2 and NH_3 is predicted. Therefore, the generation of toxic compounds as a by-product of the reaction is not anticipated.

Disadvantages

1. The process is unproven.

2. Fenton's reaction is usually performed in aqueous solutions in which explosives have low solubility.

3. The effects of the process on lagoon contents other than explosive compounds are unknown.
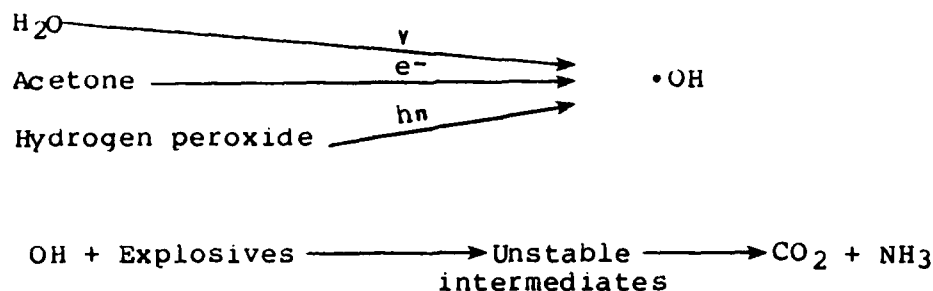
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chemical treatment is recommended as a possible initial pre-treatment step to be followed by additional processing such as fixation or other physical-chemical treatment, and ultimately in-situ closure construction.

8.3.2 Physical treatment. Atlantic Research Corporation (Wentsel et al., 1981) and Battelle (Benecke et al., 1983) evaluated several physical processes for treating explosive lagoon sediments. The most promising of the processes that were evaluated are briefly described in the following subsections. The numerous physical treatment processes available to treat nonexplosive waste materials are not addressed in this report.

8.3.2.1 Physically-induced free radical decomposition of explosives. Free radical decomposition of explosives can be induced by physical as well as chemical means. Physical methods that may be used to generate free radicals include (Wentsel et al., 1981; Benecke et al., 1983):

(a) Gamma irradiation.
(b) Electron beam processing.
(c) UV photolysis.

Once free radicals have been generated, the free radical attack and consequent decomposition of explosives is thought to proceed exactly as described in subsection 8.3.1.5, "Chemically-Initiated Free Radical Treatment." The postulated reaction chemistry is as follows:

$$H_2O, Acetone, Hydrogen\ peroxide \xrightarrow{\gamma, e^-, h\nu} \cdot OH$$

$$OH + Explosives \longrightarrow Unstable\ intermediates \longrightarrow CO_2 + NH_3$$

Source: Benecke et al., 1983.

Free radical generation by each of the three mentioned methods is discussed in the paragraphs that follow, along with the primary advantages and disadvantages of each process.

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Gamma irradiation -- In the gamma irradiation treatment process, gamma-emitting radio isotopes such as cesium-137 and cobalt-60 are used to generate hydrogen ion radicals from water or aqueous solutions of explosives. Free radical attack and decomposition of the explosives then takes place (Wentsel et al., 1981).

A summary evaluation of gamma irradiation for lagoon sediment treatment is presented in Table 42.

Electron beam processing -- Free radicals may be generated by bombarding a material with high energy electrons. This process has been proven as a sludge disinfection process and may be effective for treating aqueous solutions of explosives (Wentsel et al., 1981). The anticipated advantages and disadvantages of electron beam processing as presented by Wentsel et al. (1981) are shown in Table 43.

Ultraviolet photolysis -- Ultraviolet radiation has been shown to cause free radical-initiated decomposition of a variety of explosives in aqueous solutions in the presence of acetone or hydrogen peroxide (Andrews, 1980). The advantages and disadvantages of treatment by ultraviolet photolysis are summarized in Table 44.

8.3.2.2 Thermal treatment. Battelle (Benecke, 1983) has extensively studied thermal degradation of explosives. The results of the Battelle studies indicate that in general, relatively mild temperatures (150-300°C) and short periods of time (1 day) are required to decompose the explosives of concern to primarily gaseous and volatile compounds. Figures 64, 65 and 66 show the time and temperatures required for decomposition of explosives. Decomposition products are listed in Table 45.

Thermal treatment processes considered to be viable alternatives for in-situ lagoon treatment and closure include wet air oxidation and incineration (Wentsel et al., 1981).

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TABLE 42.   SUMMARY EVALUATION OF GAMMA IRRADIATION FOR LAGOON
            SEDIMENT TREATMENT (Adapted from Wentsel et al.,
            1981)

Advantages

1. Some data on use of gamma irradiation explosives waste
    treatment exists.

2. The process has relatively low capital and operating
    costs.

3. No major air emissions are expected.

4. Dilution of sediments to form an aqueous stream is not
    required.

Disadvantages

1. Data on use of gamma irradiation for degradation of
    high concentrations of explosives are not available.

2. Degradation products are not known. Some toxics may be
    produced.

3. Reaction rates are not known.

TABLE 43. SUMMARY EVALUATION OF ELECTRON BEAM PROCESSING FOR LAGOON SEDIMENT TREATMENT

Advantages

1. Treatment equipment is highly developed. The process has been used for sewage sludge treatment and disinfection.

2. Treatment equipment is reliable and has few maintenance requirements.

3. Treatment has relatively low operating and maintenance costs.

4. Treatment should not produce major air emissions.

Disadvantages

1. The data base for destruction of explosives or toxic materials with electron beam processing is limited.

2. Potential hazards associated with treating explosives are not known.

3. Degradation products and degradation rates are not known.

4. Processing requires dilution of the sediment so that the material can be treated as an aqueous stream.

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TABLE 44.   SUMMARY EVALUATION OF ULTRAVIOLET PHOTOLYSIS FOR
LAGOON SEDIMENT TREATMENT (Adapted from Wentsel
et al., 1981)

Advantages

1.   Explosives in the parts per million levels in aqueous
solutions have been successfully degraded.

2.   No major air emissions result from treatment.

Disadvantages

1.   Treatment capital and operating costs are relatively
high.

2.   No data exist for ultraviolet treatment of explosives
in concentrated forms (i.e., greater than the ppm con-
centrations).

3.   Full-scale treatment systems are generally not trans-
portable.

4.   Dilution of sediment to produce an aqueous stream is
required.
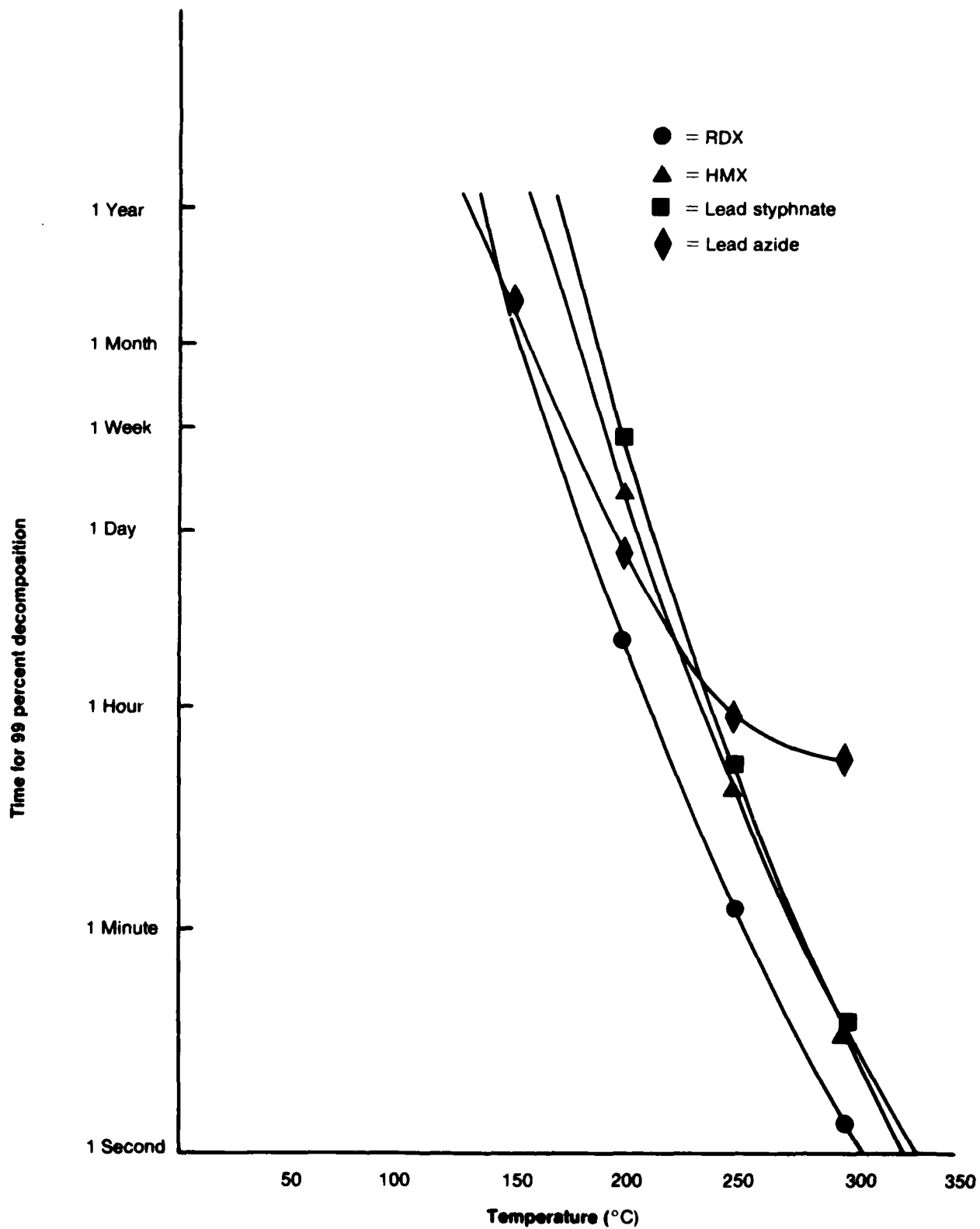
Source; Benecke et al., 1983

Figure 64.   Time versus temperature for RDX, HMX, lead
styphnate and lead azide thermal decomposition.

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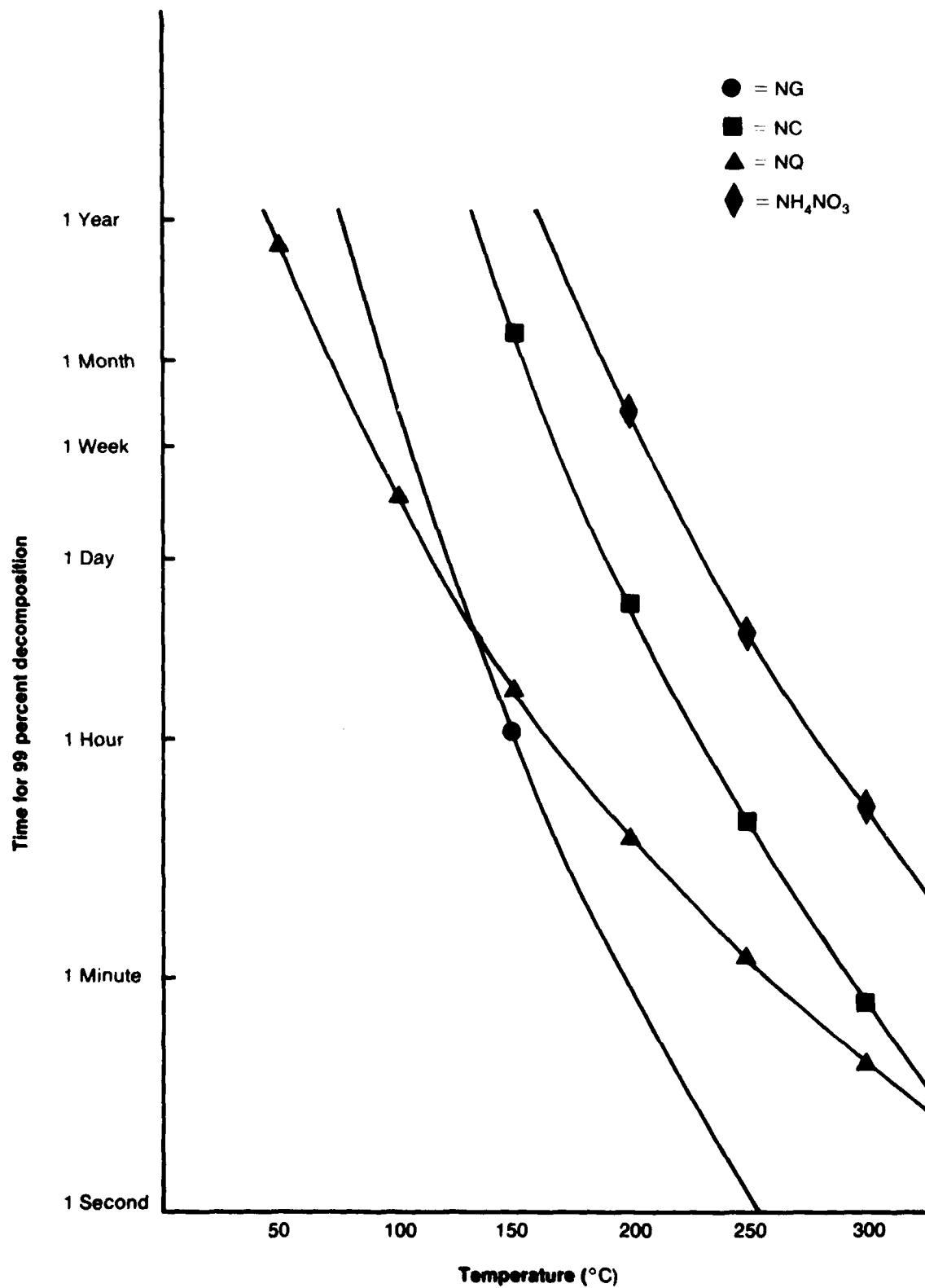
Source: Benecke et al., 1983

Figure 65.   Time versus temperature for NG, NC, NQ, and NH$_4$NO$_3$ thermal decomposition.

Source: Benecke et al., 1983

Figure 66. Time versus temperature for TNT, 2, 4-DNT, 2, 6-DNT, and tetryl thermal decomposition.

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TABLE 45. THERMAL DECOMPOSITION OF EXPLOSIVES
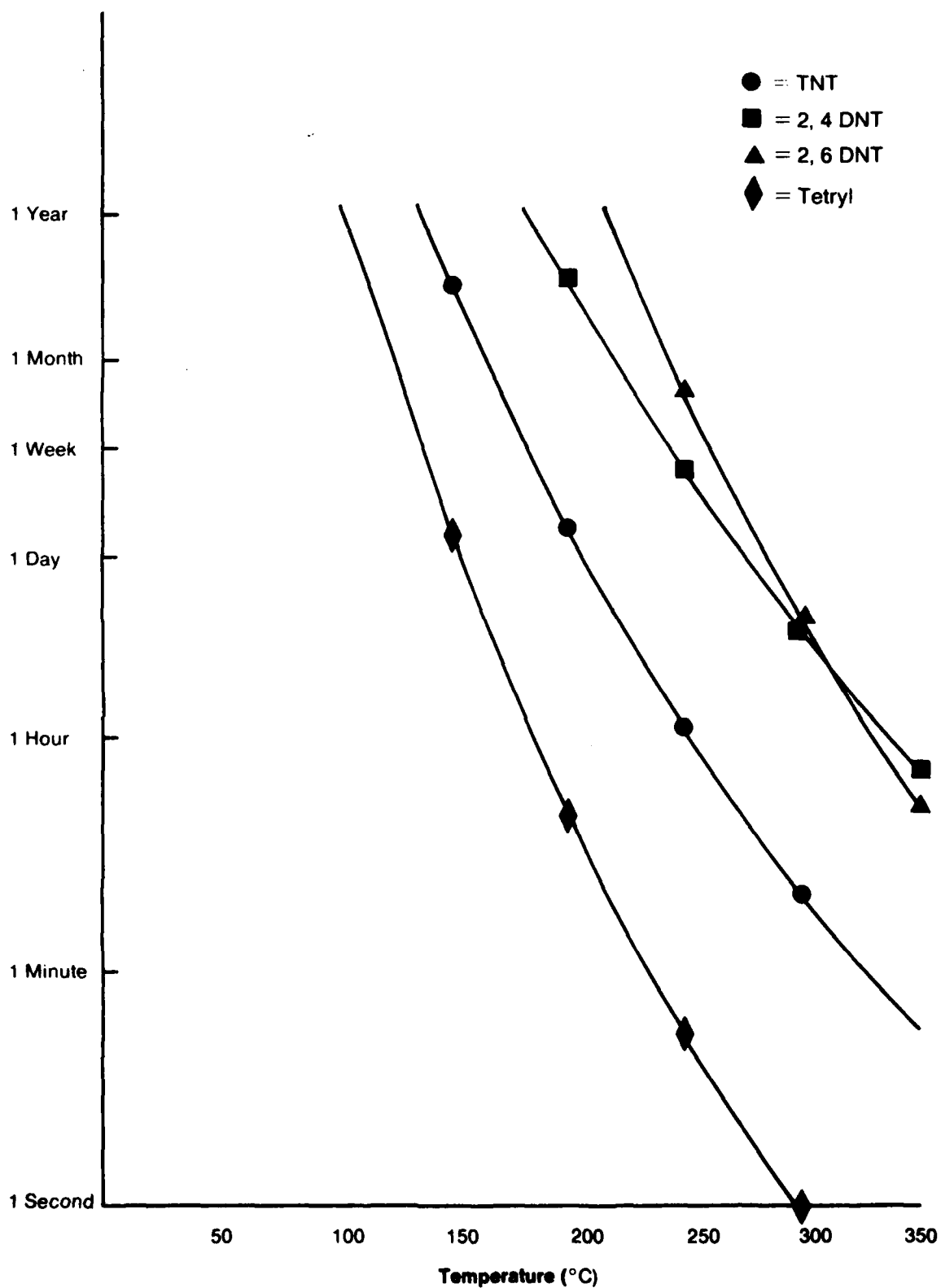
Explosives	NO$_x$	CO, CO$_2$	N$_2$, H$_2$O	CH$_2$O	HNO$_3$	Lead salts	Nitro aromatics	Minor species
RDX	X	X	X	X				NH$_3$, HCN, H$_2$, CH$_2$O$_2$, HCON(OH)Me
HMX	X	X	X	X				HCN, H$_2$, HCON(OH)Me
Tetryl	X	X	X				X[a]	
TNT	X	X	X				X[a]	C$_2$H$_2$, "explosive" coke (C$_6$H$_3$N$_2$O$_{3.75}$)
2,4 DNT	X	X	X					
2,6 DNT	X	X	X					
NC	X	X	X	X				HCN, CH$_4$, C$_2$H$_4$, H$_2$, acetates, alcohols, alde- hydes, etc.
NG	X	X	X	X	X			
NQ	X	X	X					
NH$_4$NO$_3$	X		X		X			NH$_3$, O$_2$
Lead azide			X			X		
Lead styph- nate	X	X	X			X		

[a]Intermediates.

Source: Benecke et al., 1983.

Wet air oxidation -- Wet air oxidation is a process designed to oxidize organic wastes under high temperatures and pressures to CO_2, H_2O, and inorganics. The principal components of a wet air oxidation system are a high pressure pump, heat exchanger, air compressor, and a reactor. Aqueous organic waste slurries are pumped through a heat exchanger and then into the reaction vessel where compressed air is added. Oxidation occurs in the reactor at temperatures ranging from 177 to 320°C and pressures of 1,000 to 1,800 pisa. Catalysts may be added to enhance the oxidation reaction. After being oxidized, the slurry is passed through the heat exchanger and cooled; gases are then stripped from the product stream, and waste ash is separated. The gases are treated prior to release, generally using a scrubber system.

The wet air oxidation process was evaluated by the Atlantic Research Corporation (Wentsel, et al., 1981) for treatment of explosive sediments. The findings of this study are summarized in Table 46.

Incineration -- Oxidation of explosives wastes by incineration is considered an effective means of treating lagoon sediments (Wentsel et al., 1981). A summary of Wentsel's (1981) evaluation of incineration is presented in Table 47.

8.3.3 Biological treatment. A USATHAMA-contracted literature review was completed in 1980 by Atlantic Research Corporation (Isbister et al., 1980) to evaluate the efficacy of using biological treatment to degrade explosives-contaminated lagoon sediment. Since 1980, further research in the area of explosives biodegradation has been conducted by microbiologists at Natick Laboratories (Dr. D.L. Kaplan, Dr. A.M. Kaplan, and Dr. Neil G. McCormick). The information that follows is a synopsis of the Atlantic Research Corporation literature review and the results of more recent biodegradation studies (Kaplan, 1982; McCormick, 1981). Biological treatment for lagoon closure may be employed in a landfarming-type approach, or alternatively, in a controlled reactor.

8.3.3.1 Reported results of explosives biodegradation studies.

DNT -- 2,4,-DNT is degraded relatively rapidly by mixed microbial populations with complete mineralization occurring within 1 week. With pure microbial cultures, transformation (without ring cleavage) rather than mineralization takes place, yielding some toxic amino and azoxy compounds.

2,6-DNT has not been successfully biodegraded.

TABLE 46. SUMMARY EVALUATION OF WET AIR OXIDATION FOR
EXPLOSIVE SEDIMENT TREATMENT (Adapted from
Wentsel et al., 1981)

Advantages

1. Wet air oxidation has been evaluated in bench-scale
tests for handling high levels of explosives. The proc-
ess has been shown to be effective on slurries of solid
propellants and explosives in solution. Degradation of
explosives in the 96 to 99 percent removal range, based
on COD reductions, has been achieved.

2. Heavy metals concentrations do not hinder treatment.
Metals are volatilized in the treatment process and
are effectively removed by scrubbers in the gas treat-
ment train.

Disadvantages

1. Wet air oxidation is considerably more costly than
other physical treatment processes. Relatively high op-
eration and maintenance costs are anticipated. Sediment
may build up in the reactor.

2. Treatment equipment is large and difficult to trans-
port.

3. Dilution of the sediment to produce an aqueous stream
is required.

4. Post-treatment of gases is required.

5. Ash resulting from treatment may be high in heavy met-
als and, therefore, dictates special disposal require-
ments.

TABLE 47. SUMMARY EVALUATION OF INCINERATION FOR LAGOON
SEDIMENT TREATMENT

Advantages

1. Incineration has been proven at the bench- and pilot-scale levels for effective degradation of high concentrations of propellants and explosives.

2. Transportable treatment equipment is viable.

3. No sediment dilution is necessary.

Disadvantages

1. Metals in the sediment may produce air pollutants. Air pollution abatement devices are, therefore, necessary.

2. High downtime and maintenance costs are anticipated.

3. Dewatering of wastes may be required.

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RDX -- RDX is degraded very slowly by mixed populations of aerobic microbes; anaerobic degradation takes place at a rapid rate. The anaerobic conversion of RDX takes place via denitrification pathways resulting in the production of formaldehyde, methanol, nitrogen, and hydrazines.

2,4,6-TNT -- TNT has been found to be only partially biodegradable both aerobically and anaerobically, with transformation rather than mineralization occurring. No evidence has been found for ring cleavage. Transformation products produced include some toxic compounds.

8.3.3.2 Applicability of biological processes to lagoon sediment treatment. The main problem experienced with biological degradation of explosives is that of incomplete degradation; most biological processes fail to achieve ring cleavage of the explosive molecules, thereby producing degradation products that are as potentially harmful as the explosives themselves. Typical degradation products include the following:

(a) 2,5-dinitrotoluene
(b) 3,5-dinitrotoluene
(c) 2,4-dinitrotoluene
(d) 3,4,6-trinitroethylbenzene
(e) 2,6-dinitrotoluene
(f) 2,4,6-trinitrobenzaldehyde
(g) 2,4,6-trinitrobenzyl alcohol
(h) 2,4,6-trinitrobenzoic acid
(i) 2,4,6-trinitrophenol
(j) 4-amino-2, 6-dinitrotoluene
(k) 2,4-diamino-6-nitrotoluene
(l) 4-hydroxylamine-2,6-dinitrotoluene
(m) 2,2',6,6'-tetranito-4,4'-azoxytoluene
(n) 4,4',6,6'-tetranitro-2,2'-azoxytoluene
(o) All isomers of dinitrophenols
(p) Hydrazines (Osmon and Andrews, 1978)

Until ring cleavage and complete mineralization of explosives has been achieved, biological treatment will have limited applicability for lagoon waste treatment.

The advantages and disadvantages of biological treatment of lagoon wastes is summarized in Table 48.

TABLE 48. SUMMARY EVALUATION OF BIOLOGICAL PROCESSING FOR
LAGOON SEDIMENT TREATMENT

Advantages

1. Biological processing is relatively inexpensive.

2. Under proper conditions, explosives can be biodegraded
   to nonexplosive forms.

Disadvantages

1. Some toxic end products are produced by biodegradation
   of certain explosives.

2. High concentrations of metals, if present, are toxic
   to microorganisms and will hinder biological treat-
   ment. Also, metals will not be effectively treated by
   biological processing.

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8.3.3.3 Biodegradation by genetically-engineered or conditioned microbes. Recent advances in the field of genetic engineering have shown that biodegradation of normally recalcitrant compounds has been accomplished through bioengineering (WGBH, 1982). Dr. Chackrabarty, a recognized leader in the bioengineering field, working at the University of Illinois Chicago Medical Center, has successfully grown microbes that degrade toxic wastes. Dr. Chackrabarty created the "oil eating" bacteria that was subject of the landmark Supreme Court ruling which led to the first patenting of a life form. One of his more recent accomplishments is the successful biodegradation of the defoliant 2,4-D through bioengineering.

In his work with 2,4-D, Dr. Chackrabarty collected samples of 2,4-D leachate from toxic waste dumps that contained thriving microbial populations. These microbes were cultured in the laboratory. Plasmids from other strains of microbes known to break down toxics similar in structure to 2,4-D, but incapable of breaking down 2,4-D, were added to the growing microbes. Slowly, the culture in the medium was changed so that the only carbon source available to the microbes was 2,4-D. The result of this procedure is that initially most of the microbes die, but those that do survive are able to break down 2,4-D and grow and multiply while degrading 2,4-D.

The efficacy of using techniques such as those employed by Dr. Chackrabarty to engineer a microbe to degrade DNT and TNT is largely unknown. However, based on the experience of Dr. Chackrabarty working with other recalcitrants, the possibility of success should not be eliminated.

It is anticipated that research in this field will be costly and time consuming so that degradation through bioengineering may not be a feasible alternative for immediate projects. However, this alternative should not be eliminated from consideration for use on future projects.

Poly-Bac Inc. is presently experimenting with biodegradation of explosive sediments. Results are expected in the near future (Johnson, 1983).

8.3.4 Summary. A summary evaluation of treatment alternatives for in-situ lagoon treatment and closure is presented in Table 49. Performance categories for evaluation include the following:

(a) State of technology development.
(b) Cost of treatment.

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TABLE 49. SUMMARY EVALUATION OF TREATMENT ALTERNATIVES FOR IN-SITU LAGOON TREATMENT AND CLOSURE

Alternative	State of technology development	Cost of treatment	Availability of transportable processing equipment	Effectiveness for desensitizing explosives (desensitization to non-explosive products)	Effectiveness for treating explosives (treatment to non-explosive, nontoxic products)	Effectiveness for treating composite lagoon wastes, including heavy metals, and other non-explosive lagoon constituents (treatment to non-explosive, nontoxic products)
Chemical treatment						
Sulfur-based reduction	○	○	●A	●A	○A	II
Sodium borohydride reduction	○	◐A	●A	●A	◐A	II
Base-initiated decomposition	○	○A	●A	●A	◐A	II
Reductive cleavage	○	○A	●A	II	◐A	II
Chemically-initiated free radical treatment	○	○A	●A	●A	●A	II
Physical treatment						
Gamma irradiation	◐	○A	○A	●A	II	II
Electron beam processing	◐	○A	●	II	II	II
Ultraviolet photolysis	◐	●	○	◐	II	II
Wet air oxidation (with air emissions control)	●	●	◐	●A	●A	●A
Incineration (with air emissions control)	●	◐	◐	●A	●A	◐A
Biological treatment						
Biodegradation	●	○	●	◐	○A	○A

Key

○ Low
◐ Medium
● High
A   Anticipated -- for undeveloped processes.
II Insufficient information available to make a determination.

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(c) Availability of mobile processing equipment.

(d) Effectiveness for desensitizing explosives (desensitization to nonexplosive products).

(e) Effectiveness for treating explosives (treatment to nonexplosive, nontoxic products).

(f) Effectiveness for treating composite lagoon wastes, including heavy metals and other nonexplosive lagoon constituents (treatment to nonexplosive, nontoxic products).

Alternatives are rated low, medium, or high in each of these categories.

8.4 Limitations. Various processes exist that may have benefits for improving waste characteristics or desensitizing lagoon contents. Some limitations of waste treatment and processing technology include the following:

(a) Many of the treatment processes have not been demonstrated in full-scale operations. Some of the procedures have been demonstrated in the laboratory in bench-scale using pure materials. The applicability and performance of such processes to treat waste materials in lagoons, however, remains questionable.

(b) The cost of full-scale implementation of such processes, as well as the lack of availability of commercial full-scale equipment may limit the applicability of some treatment processes.

(c) Technical limitations such as the following should be expected in the implementation of such processes:

- Some treatments could require specialized reaction vessels.
- Kinetics of treatment/desensitization reactions have not been quantified.
- Materials handling systems may be complex and require special engineering.

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